IXPE
Imaging
X-Ray
Polarimetry
Explorer

New insights on cosmic sources from X-ray polarimetry

Giorgio Matt (Univ. Roma Tre)

Plan of the talk

General introduction & IXPE

A (biased) selection of IXPE results

X-ray polarimetry beyond IXPE

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X-ray polarimetry beyond IXPE

X-ray polarimetry

Information on celestial (extra-solar) sources are mostly provided by electromagnetic radiation.

They can be obtained by studying the spatial, spectral, timing and *polarization* properties of the observed radiation.

In particular, the polarization properties give us information on *geometry* (in a broad sense: geometry of the emitting matter but also of magnetic and gravitational fields, of space-time, etc.). The polarization degree depends on the level and type of symmetry of the system, the polarization angle indicates its orientation.

Our knowledge of the emission from a celestial source in any energy band is therefore incomplete without polarimetry.

However, polarimetric information were basically missing in the X-ray band before IXPE!

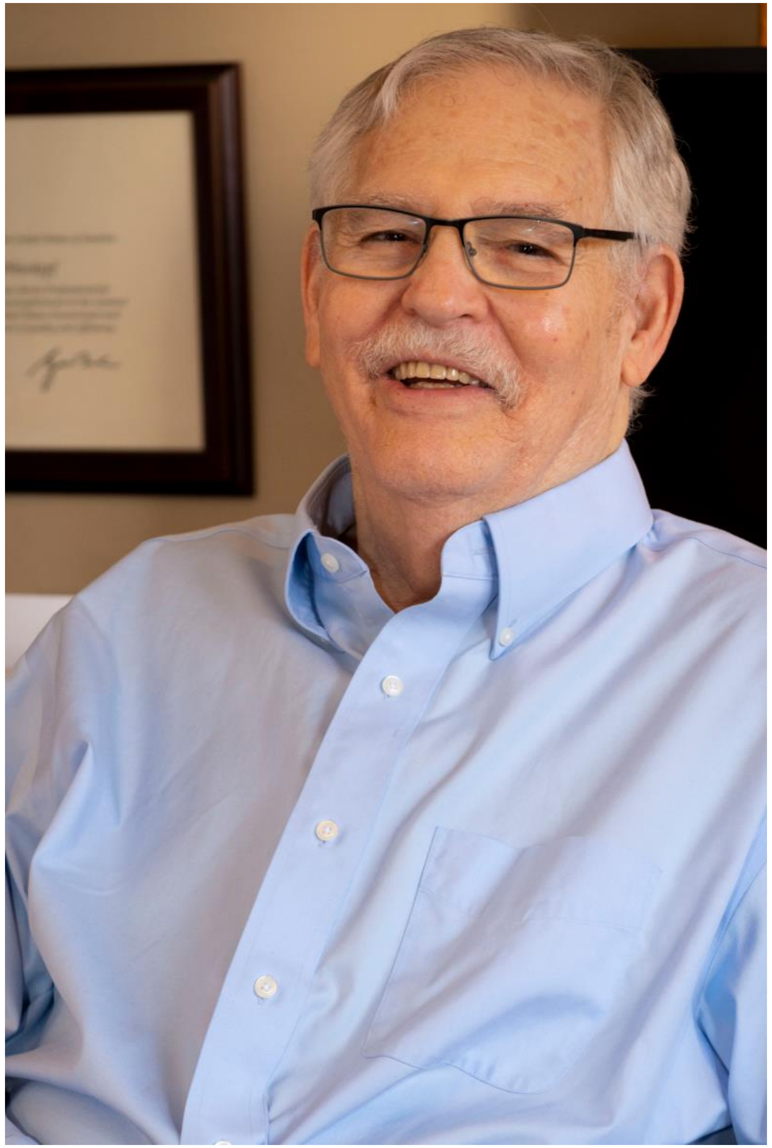
The Imaging X-ray Polarimetry Explorer (IXPE) was selected by NASA in 2017 in the framework of the SMEX program, and launched in December 2021

IXPE mission description

- A NASA/ASI mission within the NASA's Small Explorer Program (SMEX)
- Launched December 9, 2021 on a Falcon 9 from KSC
- 600-km circular orbit at a nominal 0° inclination
- 2-year baseline mission, now extended with GO program
- Point and stare (with dither) at pre-selected targets
- Malindi ground station - primary (Singapore - secondary)
- Mission Operations Center (MOC) at the University of Colorado, Laboratory for Atmospheric and Space Physics (LASP)
- Sciences Operations Center (SOC) at MSFC
- Data archiving at NASA's HEASARC – No proprietary rights, neither in the baseline phase nor in the present GO phase

PI: Phil Kaaret (former PI, until May 2022: Martin Weisskopf)

Martin Charles Weisskopf



(April 21, 1942 – May 2, 2026)

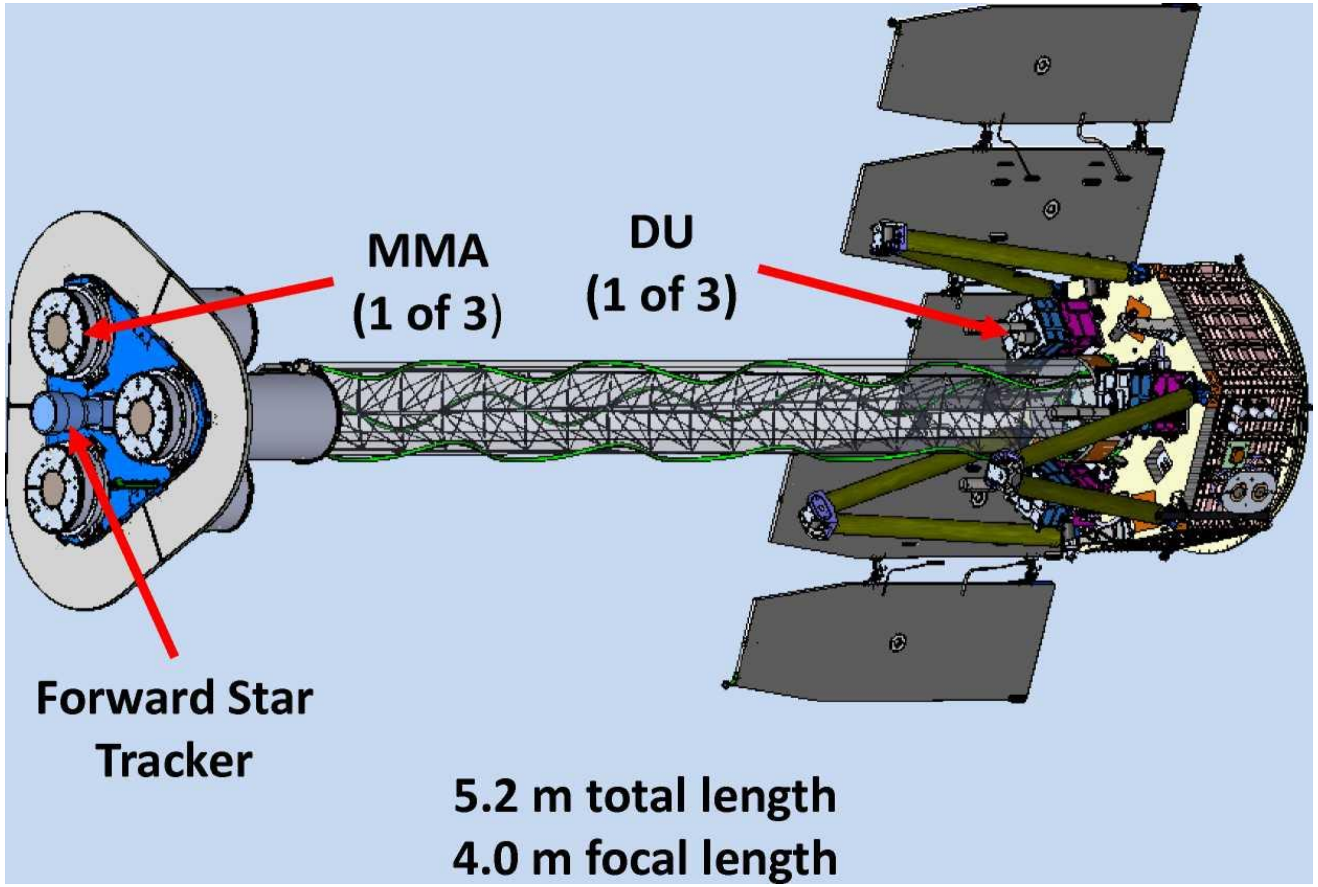
Rossi Prizes:

2004 with H. Tananbaum for the Chandra XRO

2024 with P. Soffitta and the IXPE team

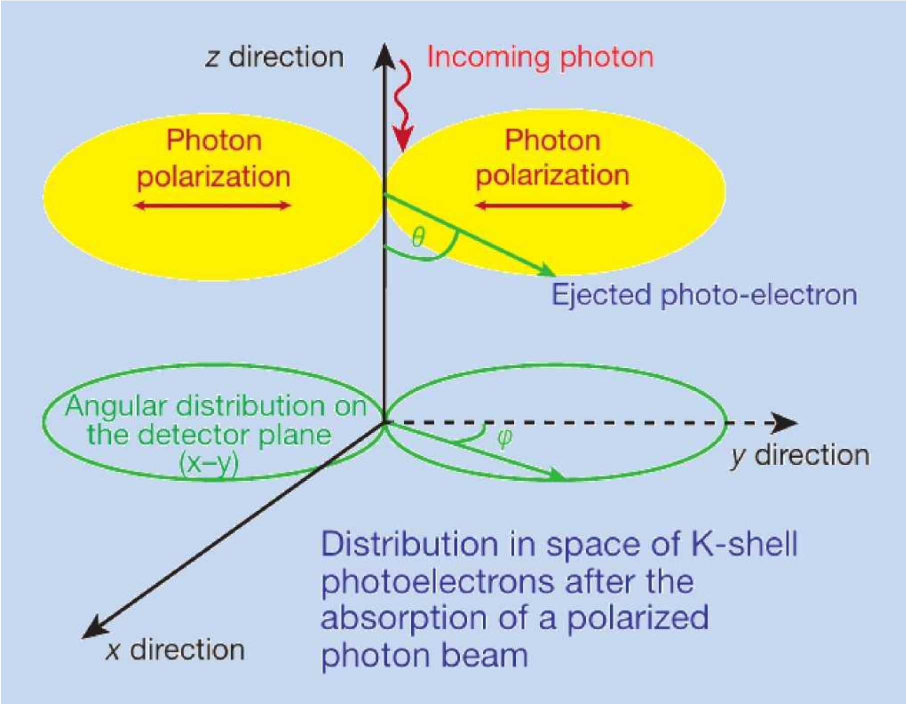
IXPE in a nutshell

- *Energy range: 2-8 keV*
- *Spatial resolution: 30'' (FWHM)*
- *FOV=13'*
- *Energy resolution: 0.57 keV @ 2 keV (FWHM)*

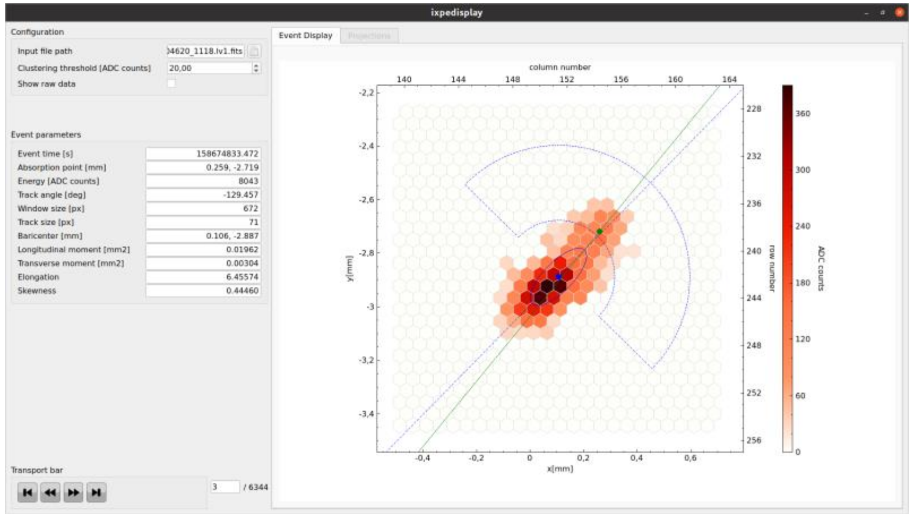


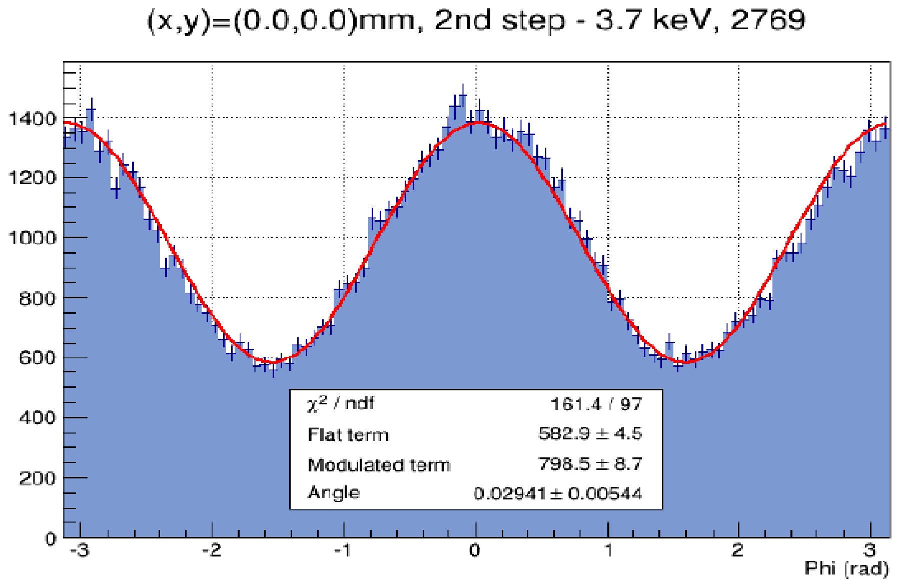
Polarization Detection Principle

The detection principle is based on the photoelectric effect



$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$





Observing Program

The IXPE baseline mission was funded for two years, and finished on January 31, 2024. Observation program defined by the IXPE team.

Extended by NASA up to 2028 (at least).

A General Observer Program now in place.

Deadline for GO4 proposals: September 17, 2026.

Joint programs with NuSTAR, Swift, XRISM, XMM-Newton (new!) and NSF/NRAO

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X-ray polarimetry beyond IXPE

IXPE results: Baseline Phase

5 PWNe and isolated pulsars	Crab PWN, Vela PWN, MSH 15-52, PSR B0540-69, G21.5
6 SNR	Cas A, Tycho's, NE SN 1006, RCW 86, RX J1713.7-3946, Vela Jr.
11 Accreting stellar-BH	Cyg X-1, 4U 1630-472, Cyg X-3, LMC X-1, 4U 1957-115, SS 433 Lobes, LMC X-3, SWIFT J1727.8-1613, 4U 1957+115, Swift J0243.6+6124, Swift J1727.8-1613
19 Accreting NS	Cen X-3, Her X-1, GS1826-67, Vela X-1, Cyg X-2, GX 301-2, X Persei, GX 9-9, 4U 1820, GRO J1008-57, XTE 1701-46, EXO 2030+375, LS V+44 17, GX 5-1, 4U 1624-49, Sco X-1, Cir X-1, GX13+1, SMC X-1
4 Magnetars	4U 0142+61, 1RXS J170849, SGR 1806-20, 1E 2259+586
5 Radio-quiet AGN & 1 Sgr A*	MCG 5-23-16, Circinus Galaxy, NGC 4151, IC 4329 A Sgr A* Complex, NGC 1068
15 Blazars & radio galaxies	Cen A, S5-0716-714, 1ES 19-59-650, Mrk 421, BL Lac, 3C 454, 3C 273, 3C 279, Mrk 501,1ES 1959-650, BL-Lac, 1ES 0229-200, PG 1553 -113, S4 0954+65, 1E 2259+586,

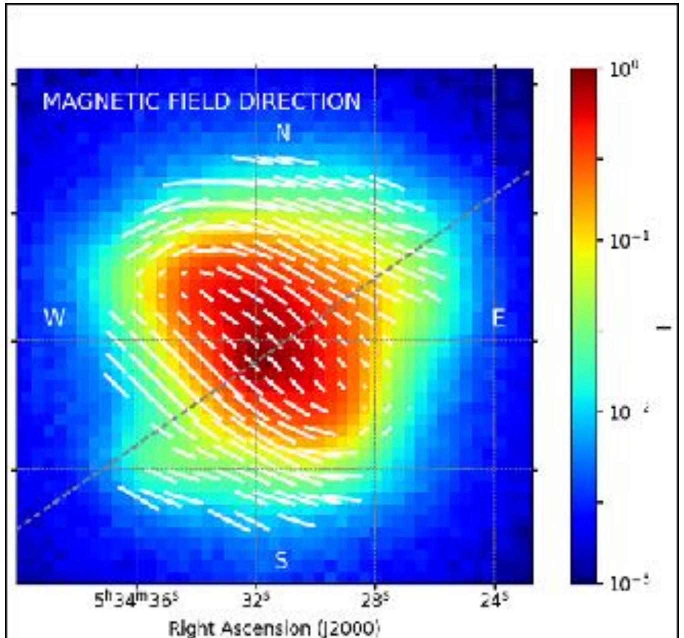
Some sources have been revisited
Mrk 421, Mrk 501, BL Lac, Vela X1, Her X-1, MCG 5-23-16, Crab, MSH 15-52, Cyg X-1, Sgr A (complex), Swift J1727, …

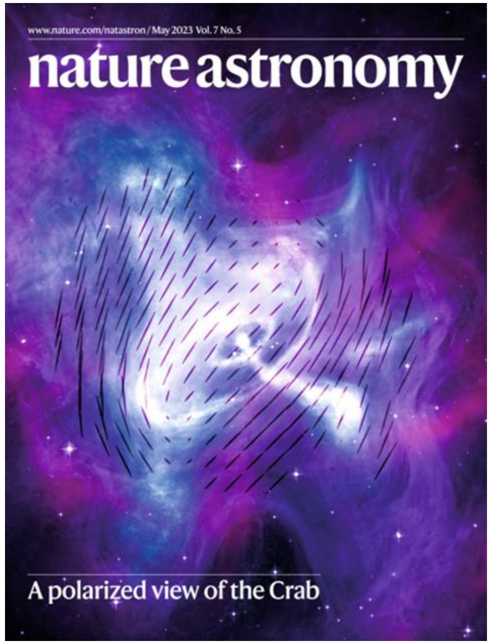
Positive detection in the majority of sources!

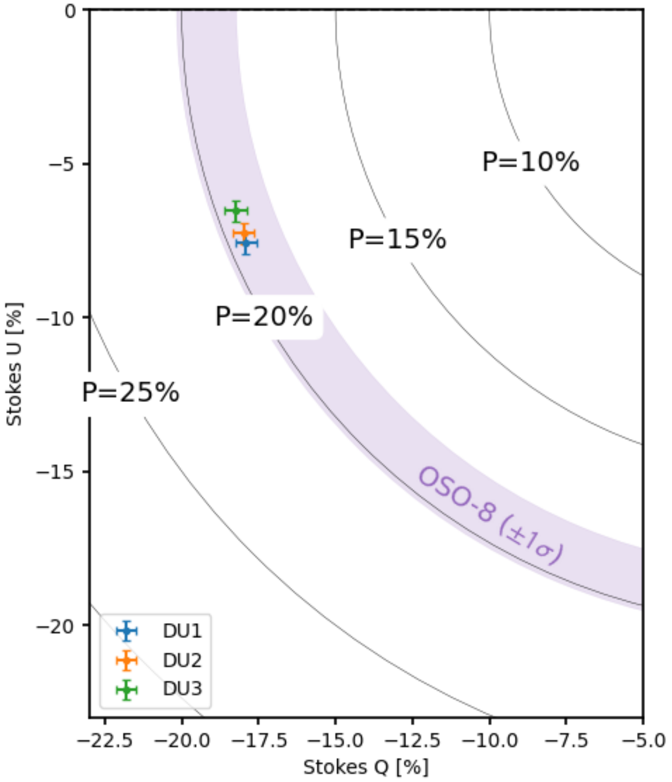
Pulsar Wind Nebulae

IXPE observations of PWN (Crab, Vela) confirmed they are highly polarized (very high in certain regions, close to the synchrotron limit) *(Bucciantini et al. 2022, Xei et al. 2002).*

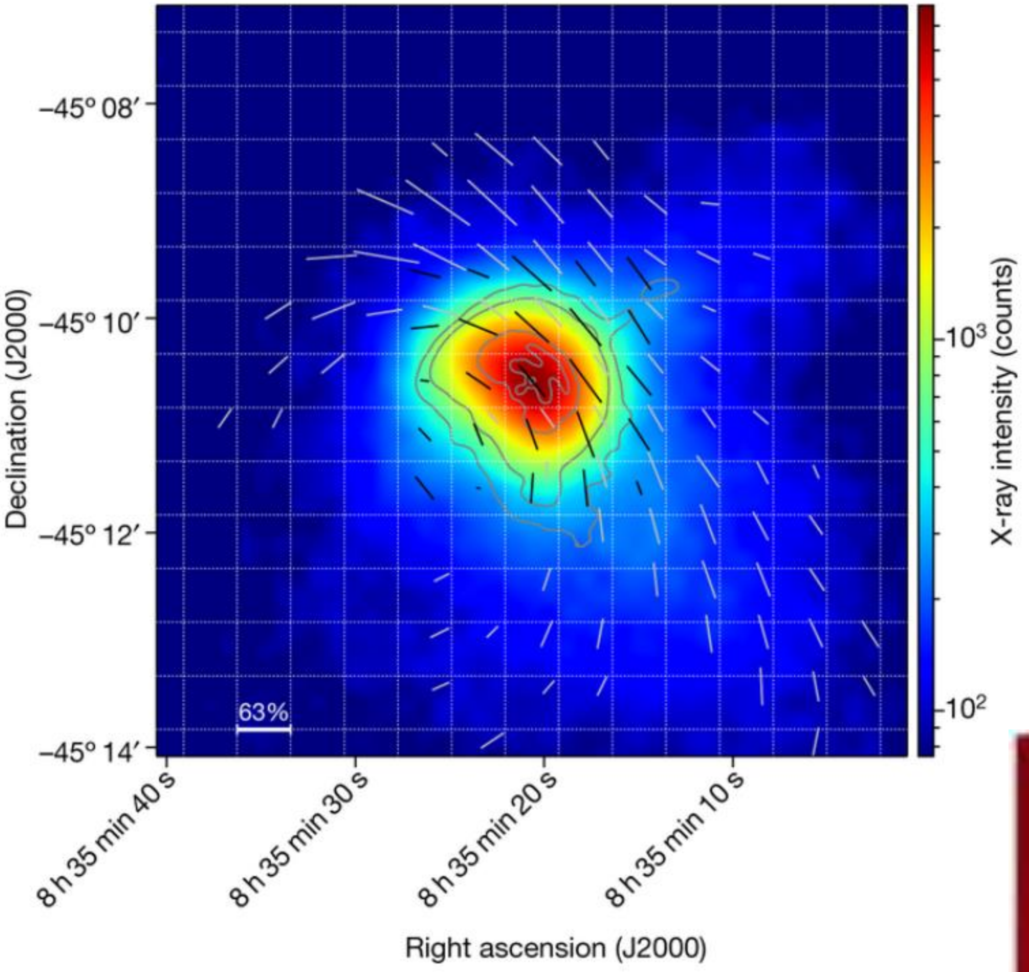
Crab result consistent with OS0-8, when integrated over the entire nebula. However, polarization map shows a complex pattern, not surprisingly given the Chandra image







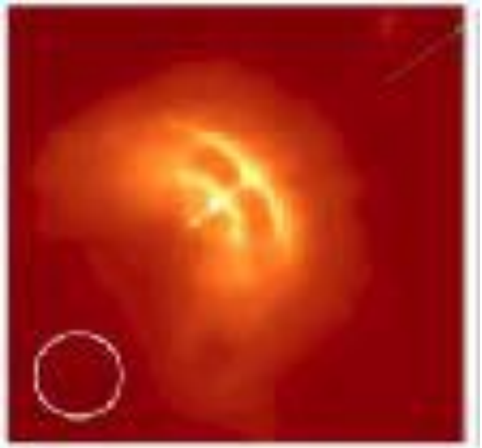
The Vela PWN



Average polarization of 45%, larger than 60% is some, small regions → close to the Synchrotron limit!

High polarization suggests B less turbulent than expected.

Polarization consistent with radio, but X-rays sample regions closer to the site of acceleration.

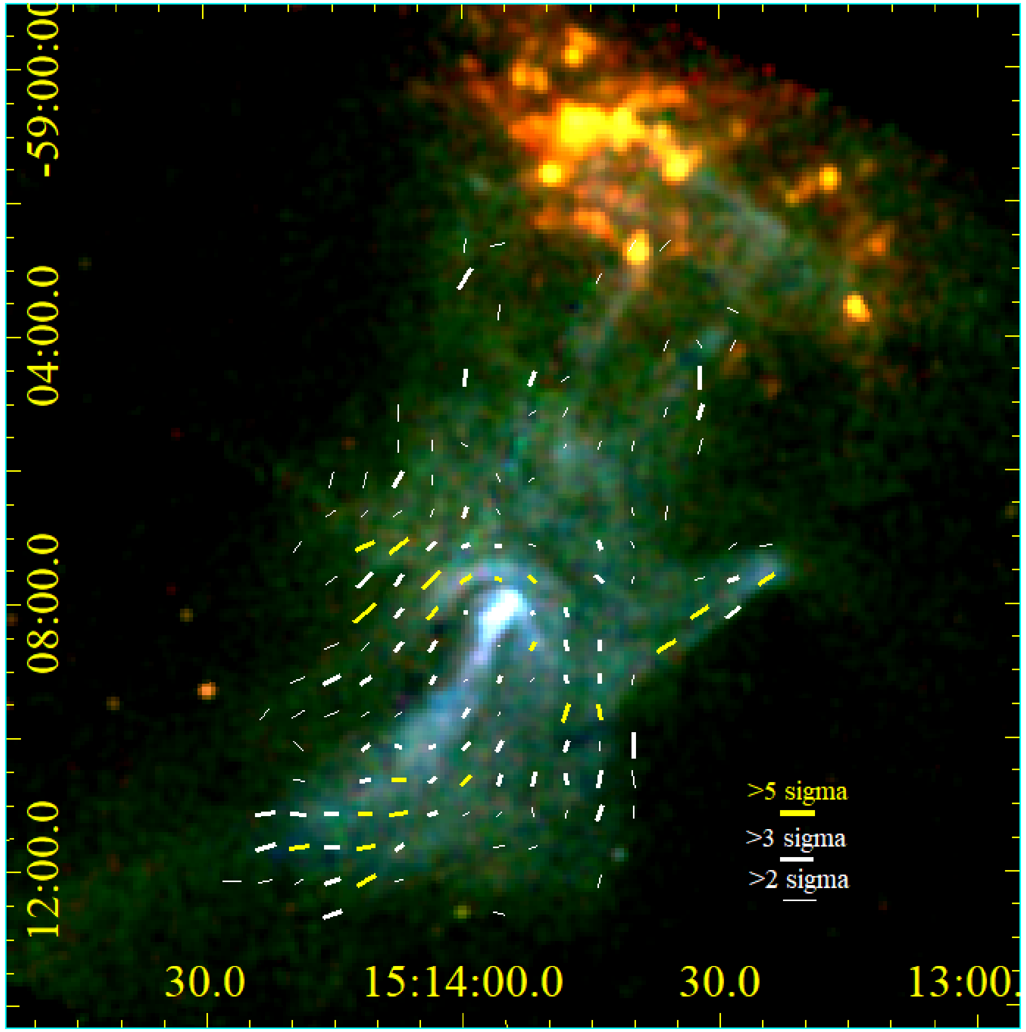


(Xie et al. 2022)

PWN: MSH 15-52 (Cosmic Hand)

Highly significant polarization in arcs and at the end the jet, with PD>70% *(Romani et al. 2023)*

Smaller polarization at the base of the jet, indicating a more complex magnetic field.

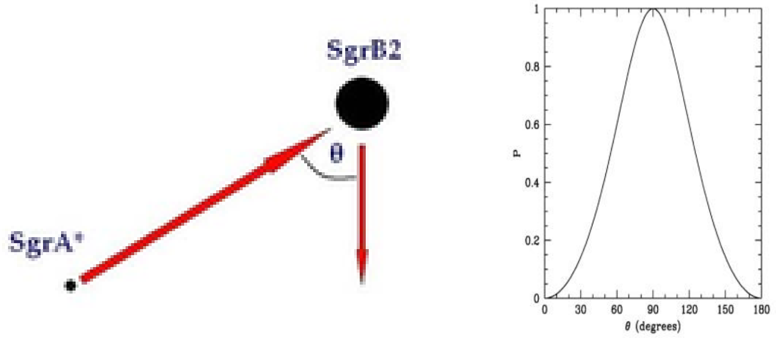


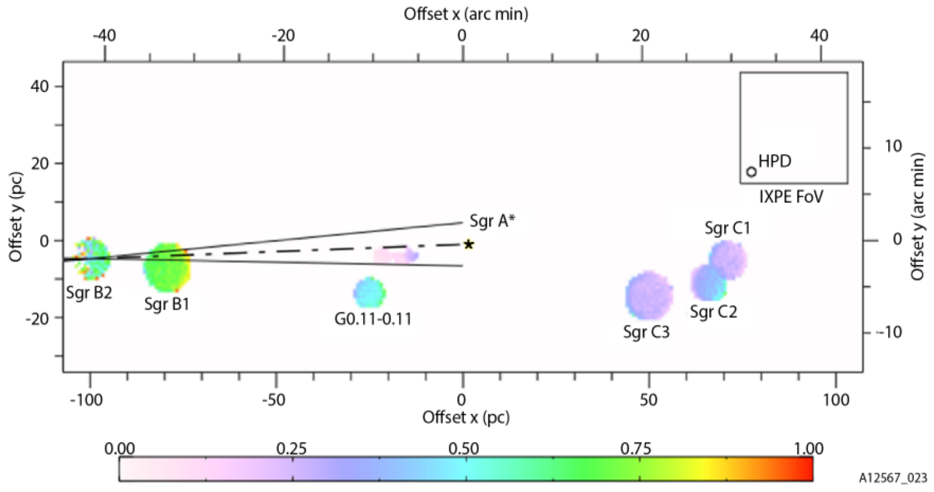
Sagittarius A*

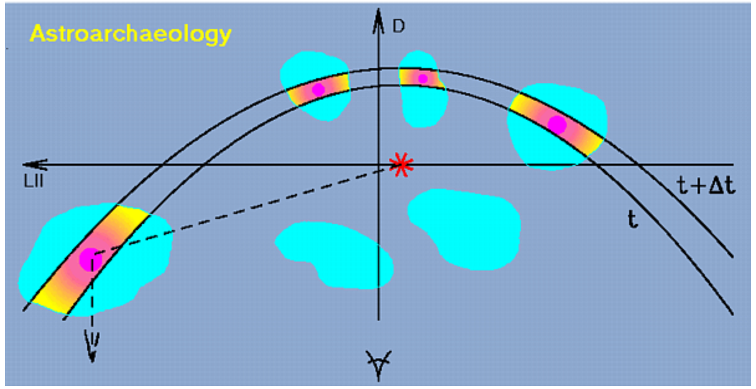
Galactic Center molecular clouds (MC) are bright X-ray sources.
Their X-ray spectra indicate reflection from external sources

Are they reflecting X-rays from Sgr A* ?
If so, Sgr A* X-ray luminosity was 10^6 larger a few hundred years ago

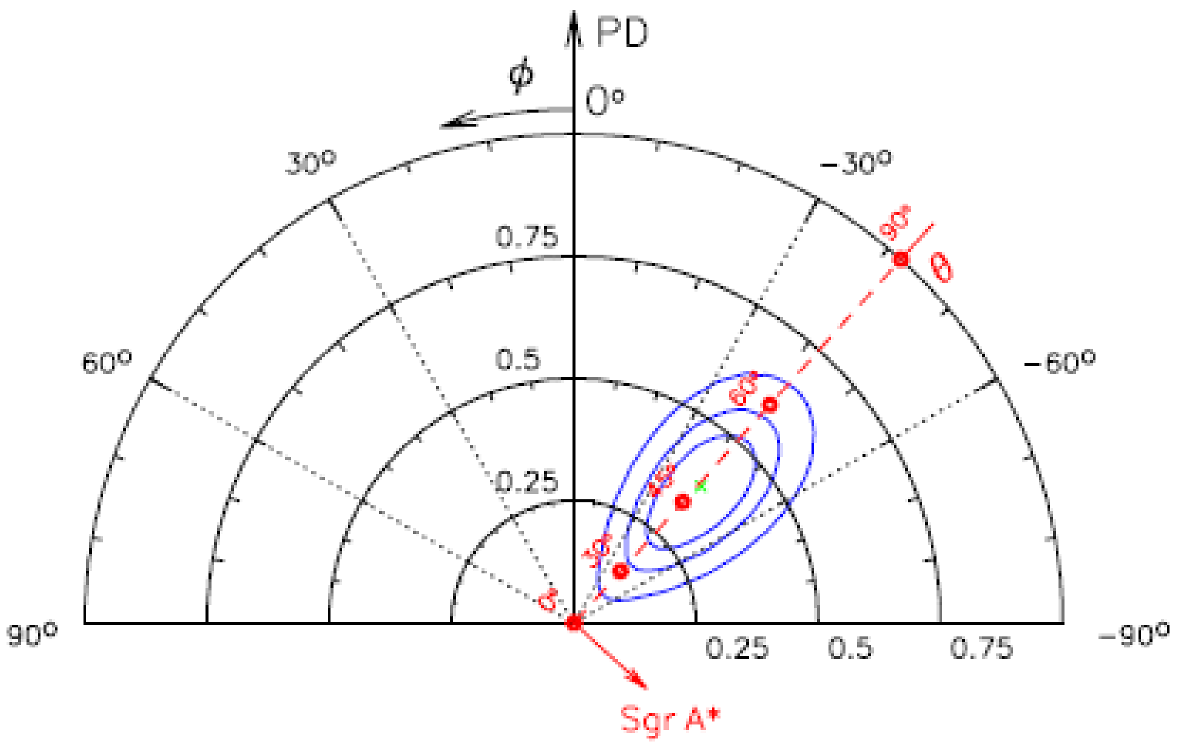
In this case, X-rays should be *highly polarized* perpendicular to plane of reflection and indicates the direction back to Sgr A*







Sagittarius A*



2.7σ result. Polarization angle consistent with Sgr A* as the origin of the illuminating radiation *(Marin et al. 2023).* A second observation confirmed the result with a ~4σ confidence level (*Khabibullin et al. 2026*)

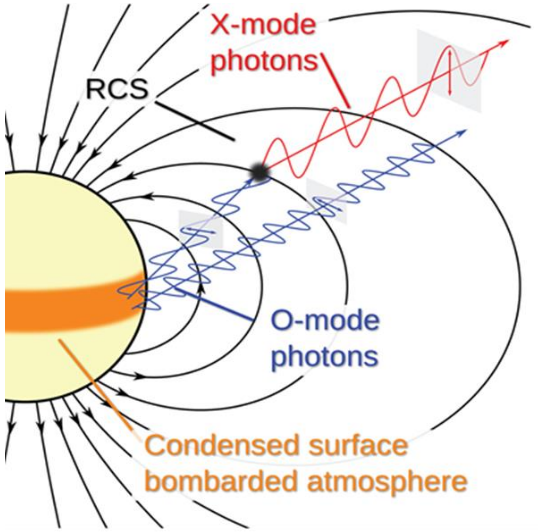
From the polarization degree, two solutions for the age of the burst: ~30 or ~200 years ago. Second solution much more probable.

But different PA in smaller, central region. Multiple sources?

Magnetars

Taverna et al. 2022

- **Anomalous X-ray Pulsars and Soft-gamma ray repeaters**
  - $B_{sd} \approx 10^{14} - 10^{15}$ G
  - $L_{X,\mathrm{persist}} \approx 10^{33} - 10^{35}$ erg s^{-1} (typically $< \dot{E}_{\mathrm{rot}}$)
  - Bursting activity (short bursts – intermediate/giant flares)
  - Two components (thermal and PL) spectra

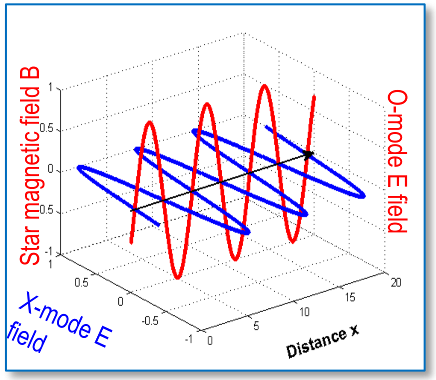


  - **Powered by their own magnetic energy**

Two modes, with very different opacities

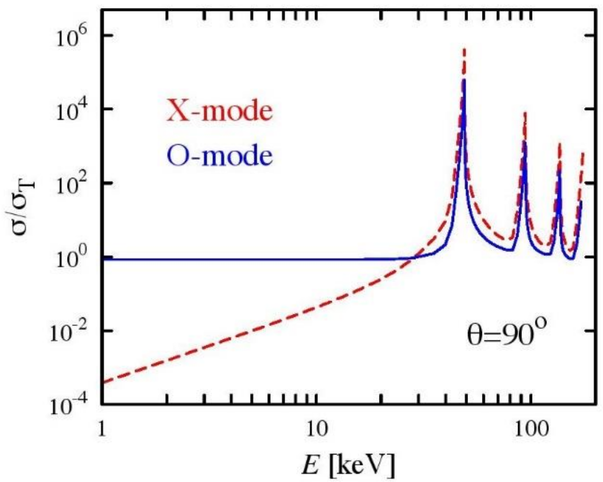
- Ordinary mode: E field parallel to the k-B plane
- Extraordinary mode: E field perpendicular to the k-B plane

The X-mode from deeper, hotter layers



O-mode:

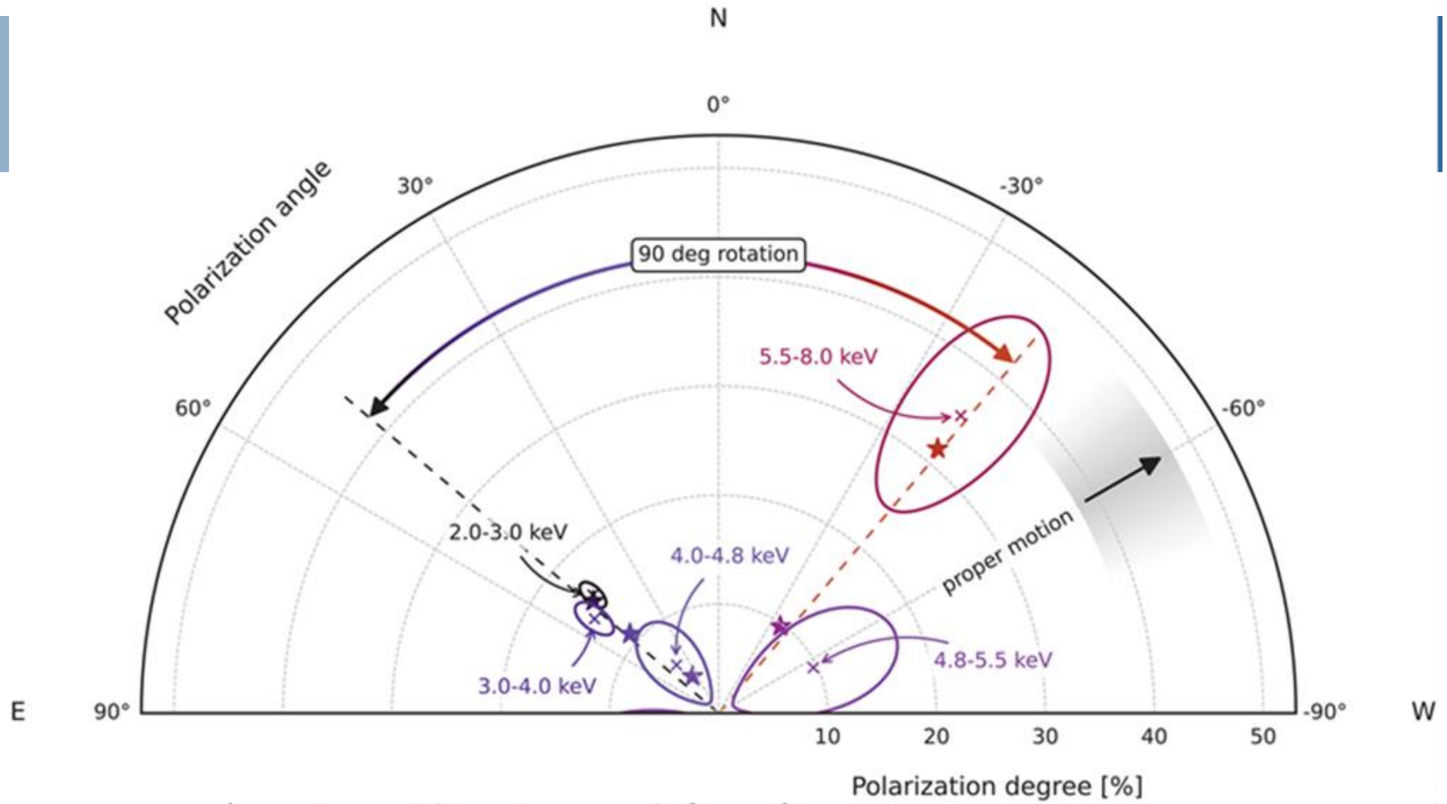
X-mode:

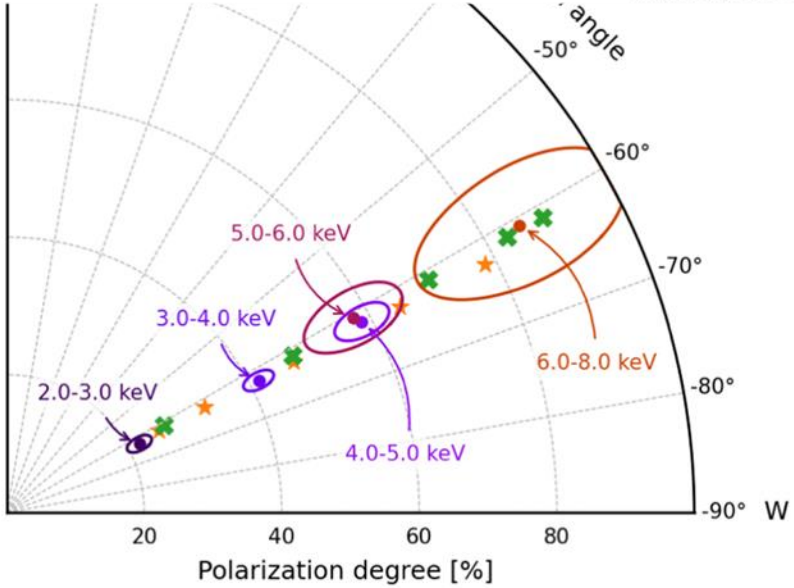


Magnetars

4U0142+61 shows PA swing of 90° (top) *(Taverna et al. 2022).* Two different modes dominate in the two components (Thermal + Resonant Compton Scattering). Low polarization indicates a condensed surface.

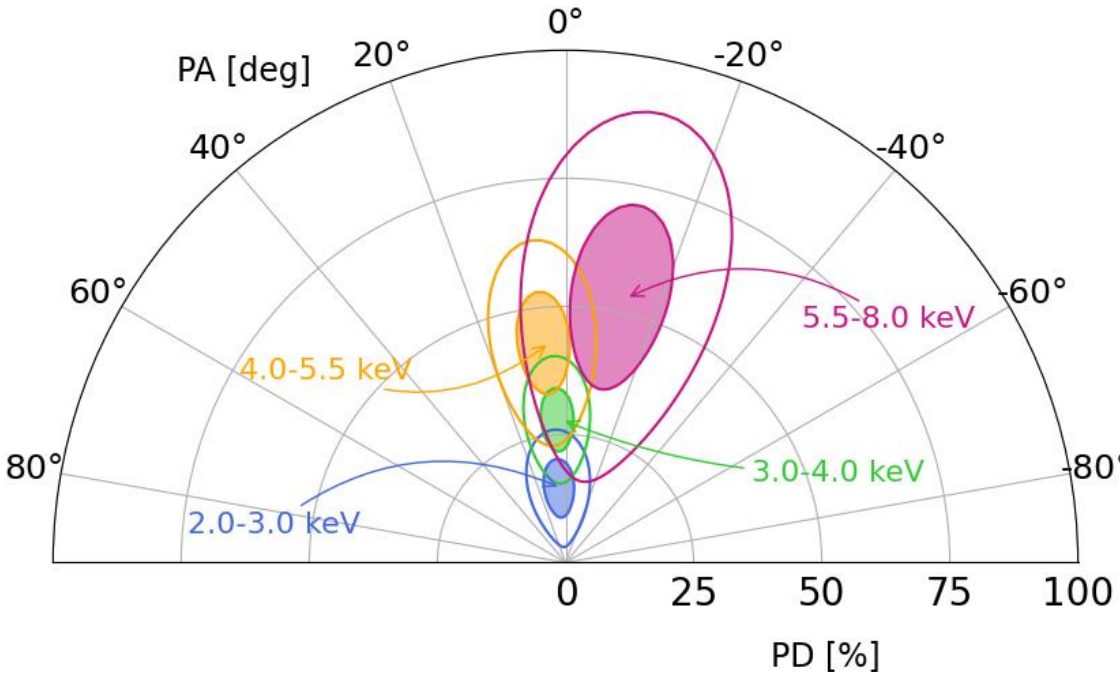
1RXS J170849.0-400910 has constant PA *(Zane et al. 2023).* The same mode is dominating in the two spectral components (both thermal). Pulse-phase-resolved data indicate condensed surface, plus a hotter cup covered by a gaseous atmosphere.

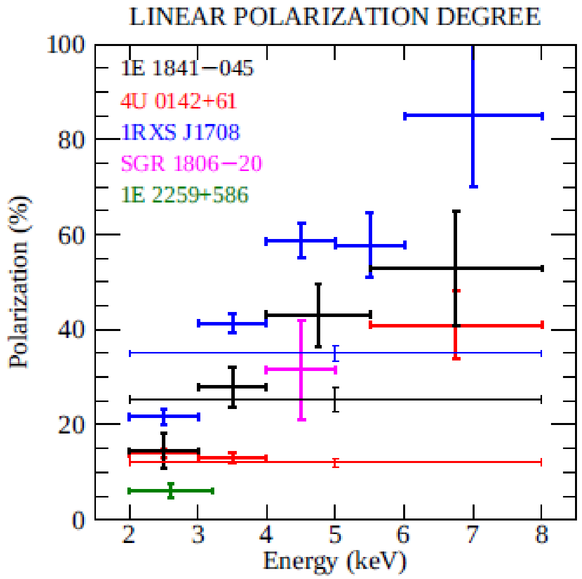


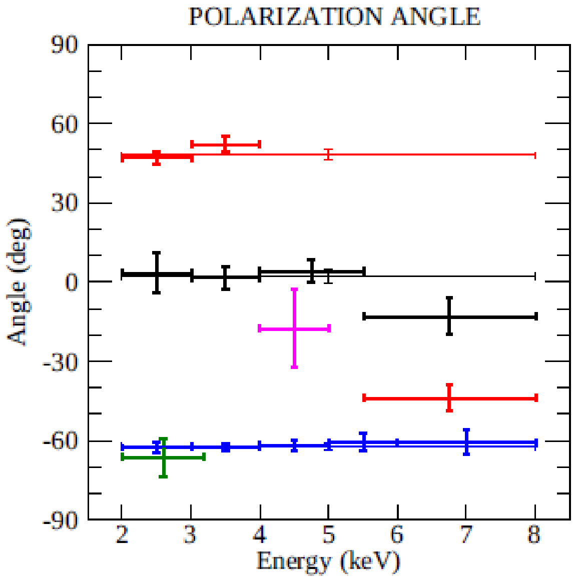


Magnetars

1E 1841-045 has also a constant PA *(Rigoselli et al. 2025, Younes et al. 2025).* Spectropolarimetrc analysis suggests a soft thermal component (PD≈25%), an intermediate resonant Compton scattering (PD≈30%) and a hard tail with PD≈65%, probably of Synchrotron origin





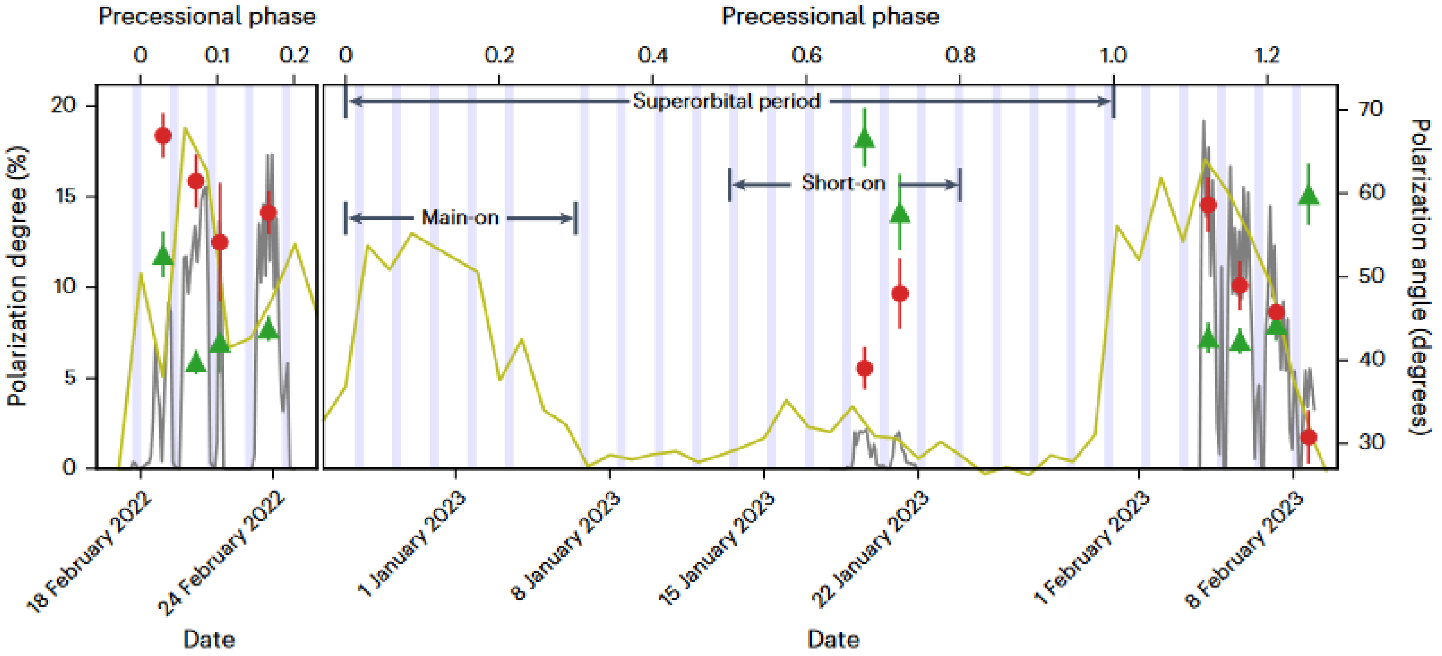


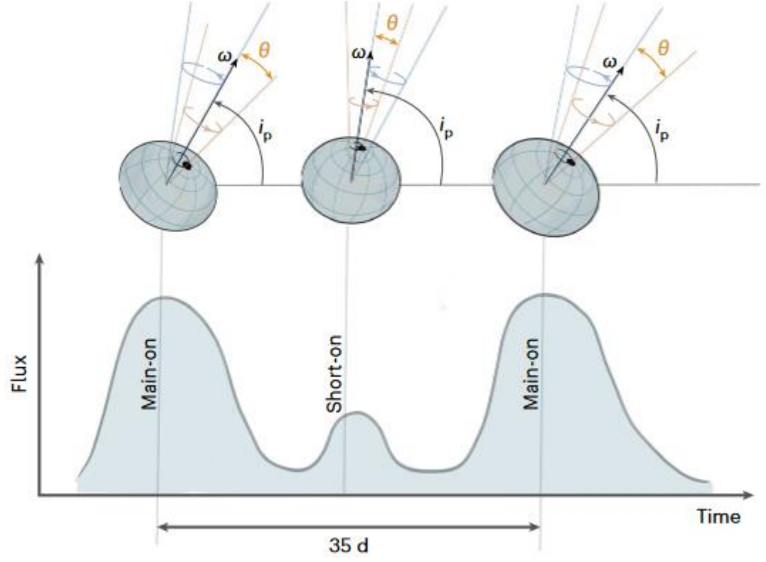
Rigoselli et al. (2025)

Accreting NS – X-ray Pulsars

Phase dependent polarization observed in many X-ray pulsars, even if with polarization degrees less than predicted by old (probably too simple) models. Important geometrical parameters can be inferred.

In Her X-1, a 35d superorbital period is observed, explained as a precession of either the neutron star or the accretion disc. IXPE results suggest that the crust of the neutron star is indeed precessing, probably exciting the precession and warping of the disc (Heyl et al. 2024)





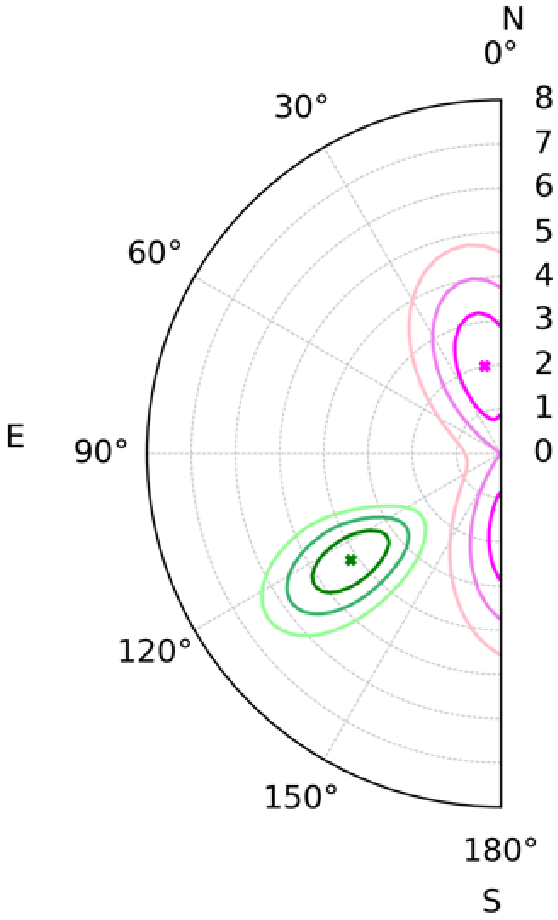
See talk by Sergey Tsygankov

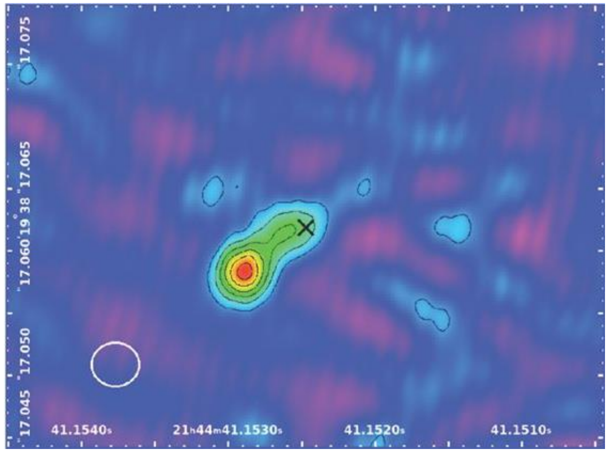
Weakly Magnetized Accreting NS

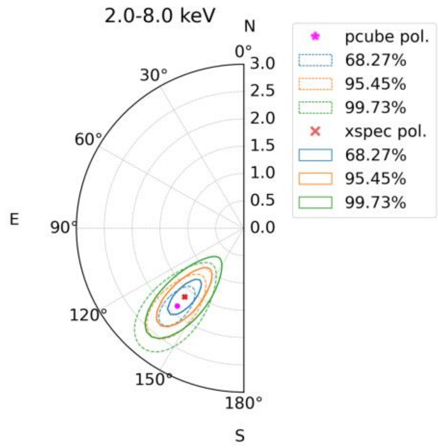
Non-pulsating accreting NS were expected to have low polarization

Surprisingly, many of them show significant (and sometimes large) polarization, often increasing with energy, and depending on the observed branch in the color-color diagram

See talk by Alessandro Di Marco

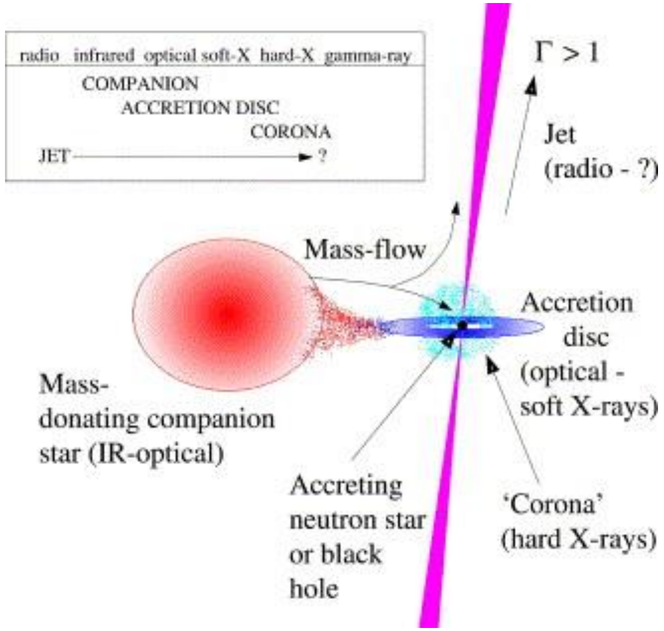


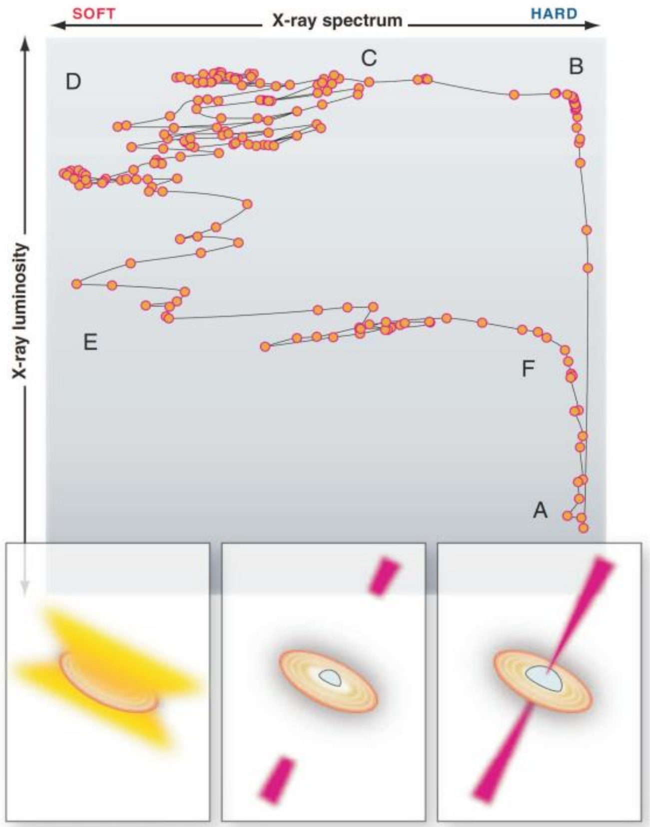




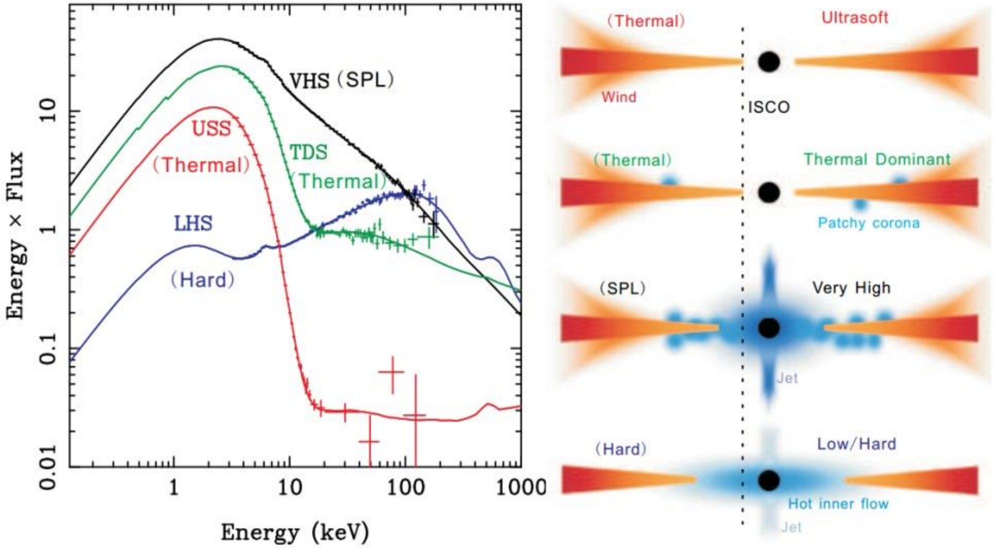
Cyg X-2 (Farinelli et al. 2023)

Accreting Stellar-mass BH





Fender & Belloni 2012



Done et al. 2007

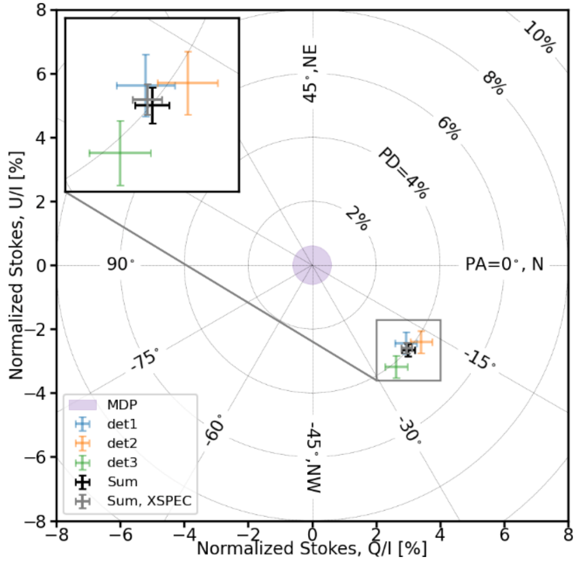
Accreting Stellar-mass BH

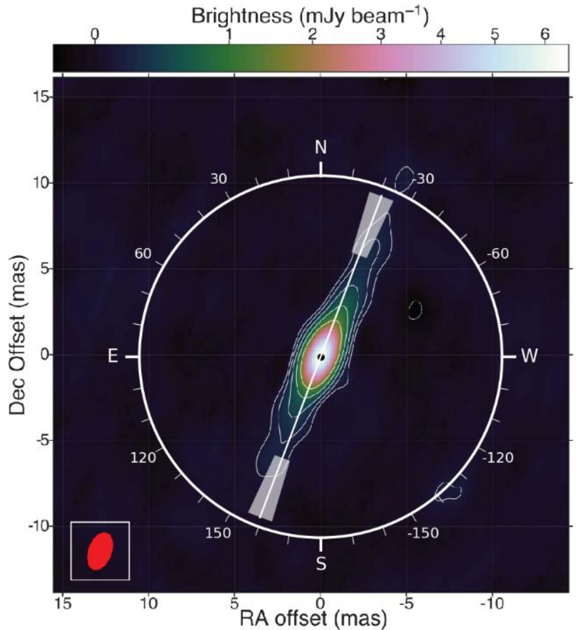
Many sources observed, both persistent and transient

Different states explored (sometimes in the same source)

Often surprising (and sometimes very puzzling) results

See talk by Alexandra Veledina

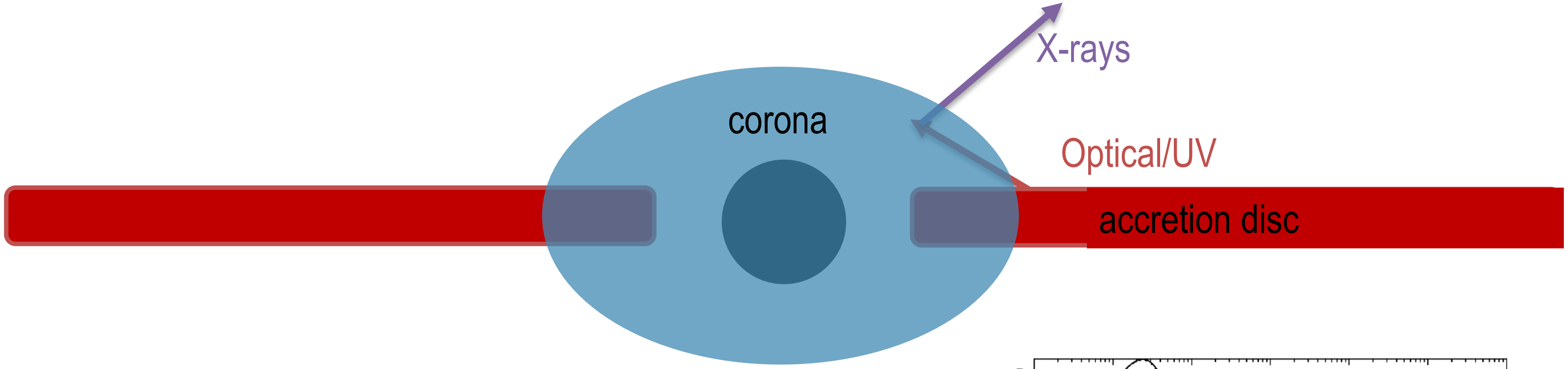




Cyg X-1 (Krawczynski et al. 2022)

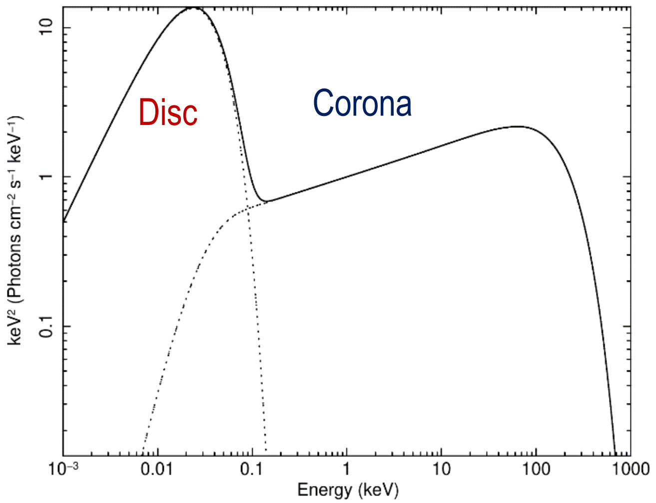
Radio Quiet AGN

In AGN the primary X-ray emission is due to Comptonization by electrons in a hot corona of the UV/soft X-ray disc photons (Shapiro et al. 1976; Sunyaev & Titarchuk 1980; Haardt & Maraschi 1991)



Cutoff power law $F_E \sim E^{-\Gamma} \exp(-Ec/kT)$
$\Gamma = \Gamma(kT,\tau)$, while Ec depends on kT

Temperature kT ~ 10-100 keV
Thomson optical depth ~ 1



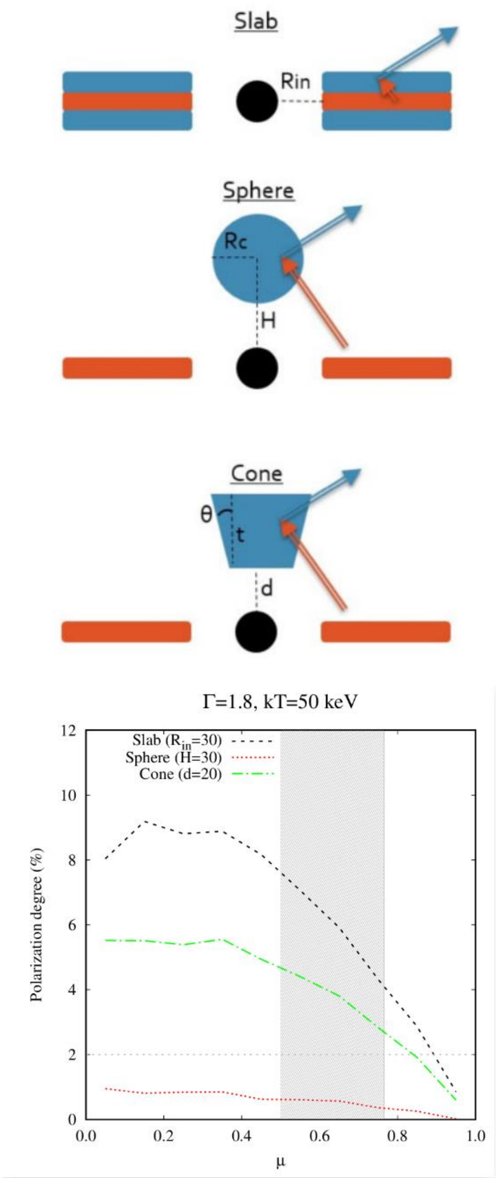
Radio Quiet AGN

X-ray spectroscopy can constrain the physical parameters of the corona.

However, it is almost insensitive to its shape and location.

Polarimetry, on the contrary, is very sensitive to the geometry of the corona, and can measure deviations from a spherical symmetry.

The coronal geometry is related to its physical origin.



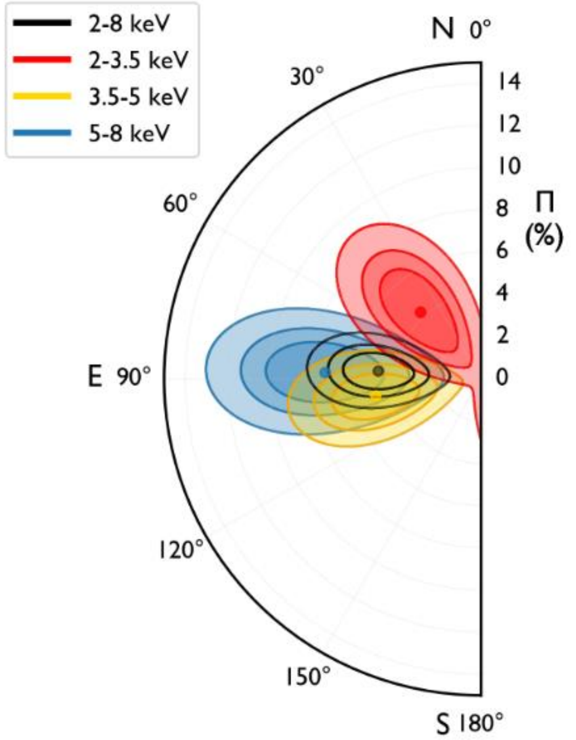
Radio Quiet AGN

Positive detection in NGC 4151 (*Gianolli et al. 2023*). 2-8 keV PD=4.9±1.1%, aligned with the radio jet. Coronal polarization in between 4 to 8%, depending on the (poorly constrained) polarization of the reflection component. Slab or wedge preferred (as for Cyg X-1).

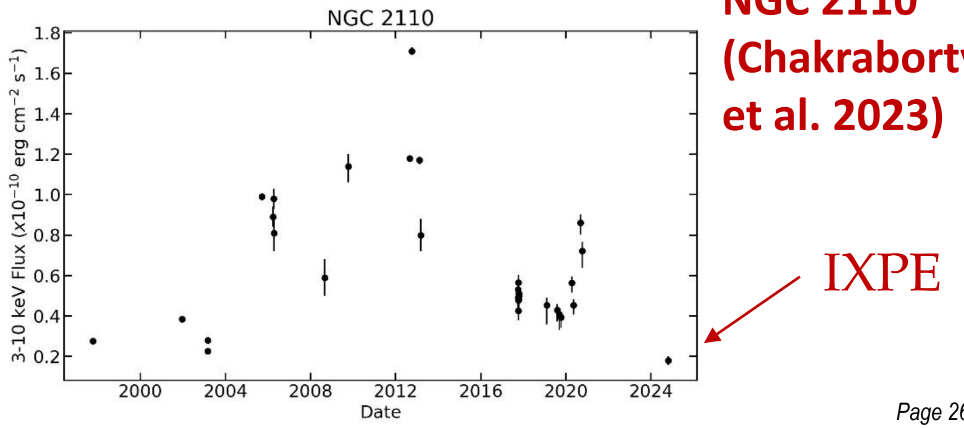
A marginal (2.97σ) detection (PD=3.3%) for IC4329A (*Ingram et al. 2023*), only an upper limit (PD<3.2%) for MCG-5-23-16 (PD <2.5%, *Marin et al. 2026*).

NGC 2110 was caught in a very low flux state, unfortunately (*Chakraborty et al. 2025, Pal et al. 2025)*

Other sources (NGC 3227, Ark 564, MCG-6-30-15) just observed (or to be observed soon)



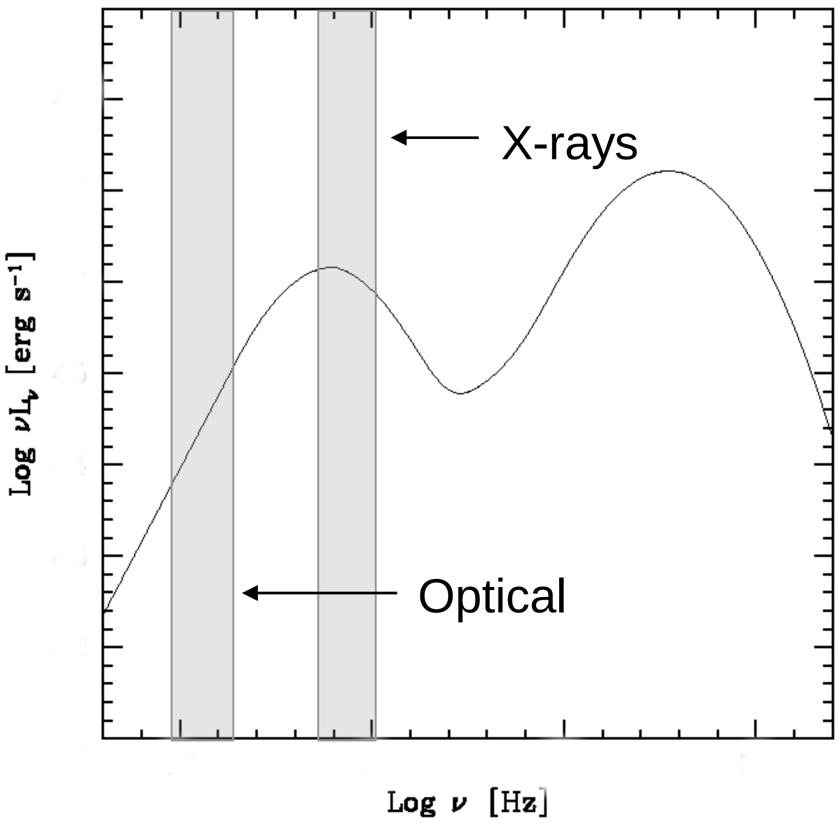
NGC 4151 (Gianolli et al. 2023)



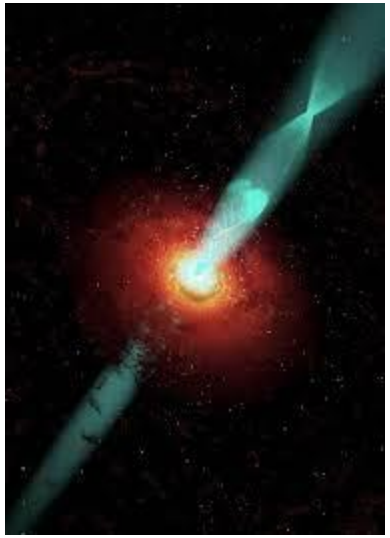
NGC 2110 (Chakraborty et al. 2023)

Blazars

High Synchrotron Peaked

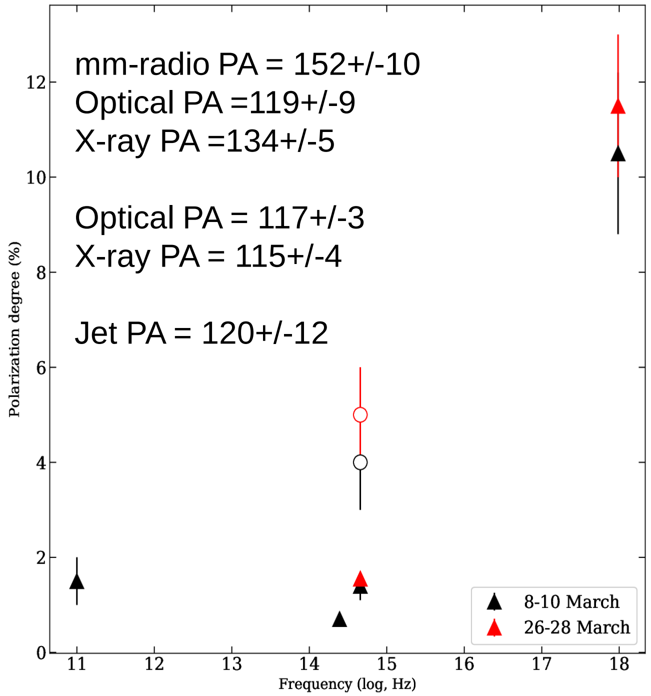


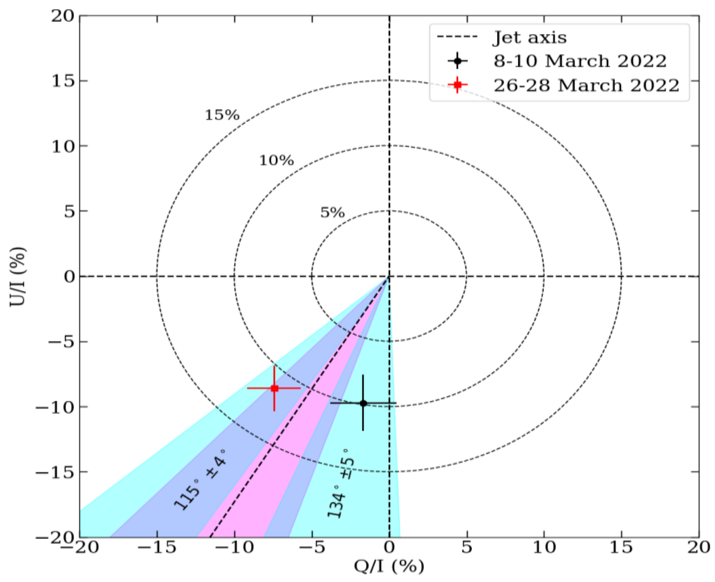
Blazars are obvious targets for X-ray polarimetry. High Synchrotron Peak Blazars like Mrk 501 (*Liodakis et al. 2022*) and Mrk 421 (*Di Gesu et al. 2022*) are indeed significantly polarized. Multifrequency observations permit to discriminate among models.

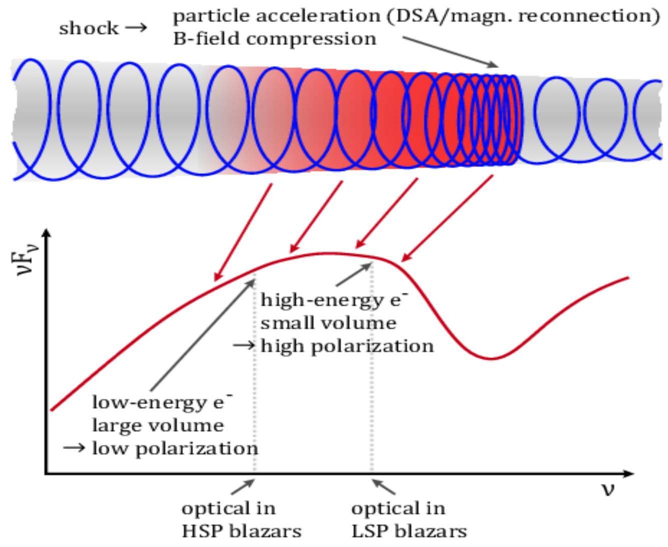


IC peak sources are instead much less polarized, and only upper limits are found (e.g. Cen A, *Ehlert et al. 2022,* BL Lac*, Middei et al. 2022, Agudo et al. 2025*). But, again, multifrequency observations permit to discriminate among models.

Mrk 501





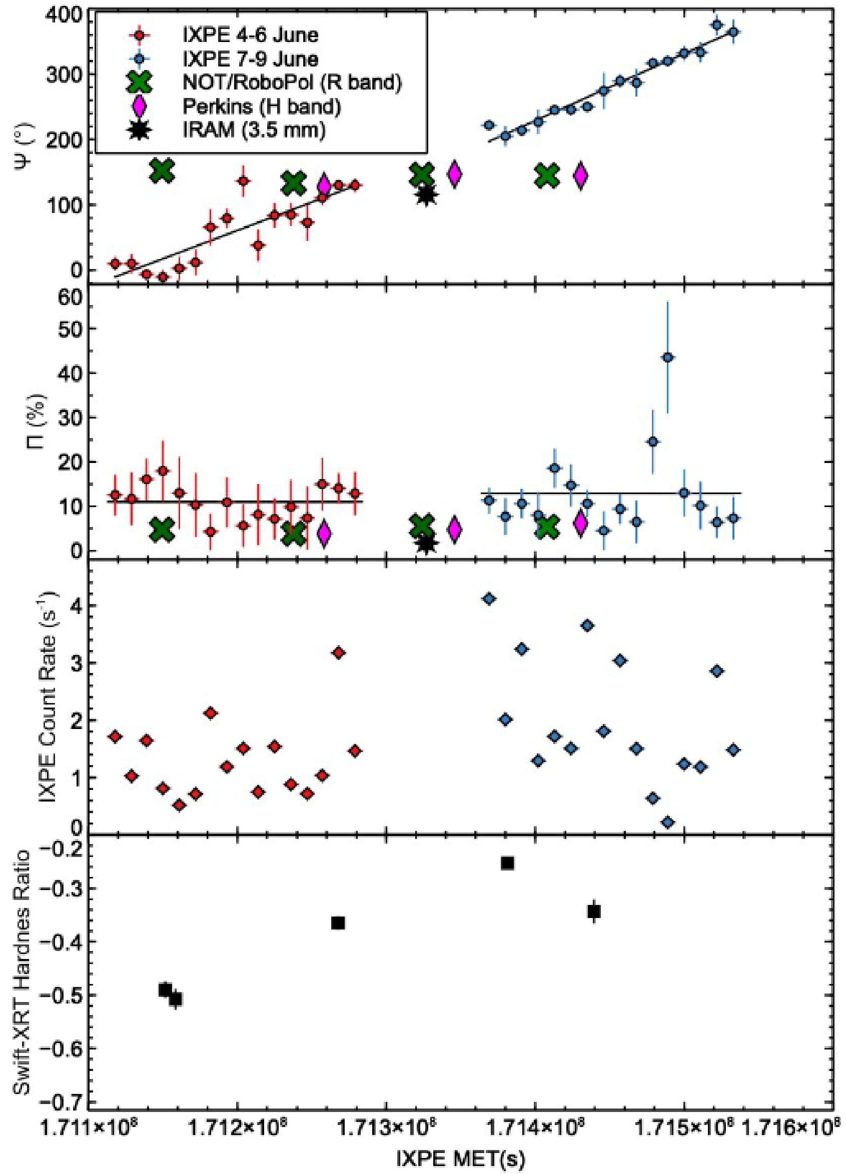


Model	Multiwavelength polarization	Variability†	Polarization angle
Single zone	constant*	moderate	any
Multizone	mildly chromatic	high	any
Energy stratified (shock)	strongly chromatic	slow	along the jet axis
Energy stratified (magnetic reconnection)	constant	moderate	perpendicular to jet axis
Observed	strongly chromatic	slow	along the jet axis

Mrk 421

Very similar results, and very similar conclusions, for Mrk 421 (di Gesu et al. 2022) …

… but in another observation of this source a continuous rotation of the polarization angle by more than 360 degrees in 5 days is detected (di Gesu 2023). A localized shock propagating along a helical magnetic structure in the jet?



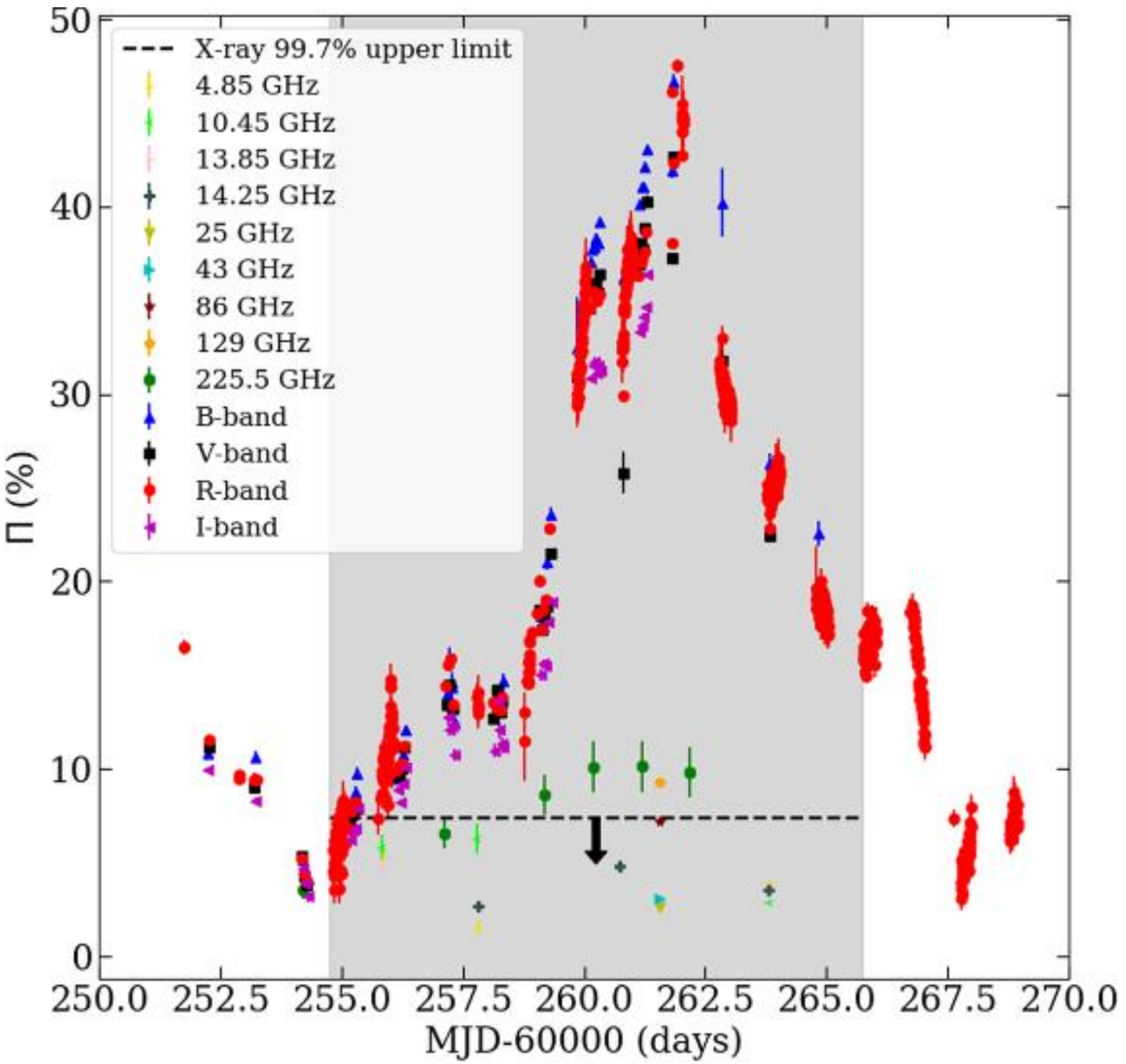
BL Lac

BL Lac was reobserved in Nov 23 during a multifrequency campaign, and caught an extraordinary event in which the optical linear polarization reached a PD of 47.5%.

Even only an upper limit could be obtained from IXPE data, the optical-to-X-rays ratio of polarization degrees is very constraining, strongly favouring a leptonic scenario (Compton scattering)

Table 1
Summary of the Multiwavelength Polarization Expectations for Different X-Ray Emission Scenarios Outlined in the Text

Model	X-Ray Polarization Degree	X-Ray Polarization Variability
Single-zone leptonic (EC)	Unpolarized	...
Single-zone leptonic (SSC)	$0.5 \times \Pi_O$	Similar to optical
Energy-stratified/multizone leptonic (SSC)	$\leqslant 0.3 \times \Pi_O$	Similar to millimeter
Single-zone hadronic	$\approx \Pi_O$	Less variable than optical
Energy-stratified/multizone hadronic (flare)	$\approx \Pi_O$	Less variable than optical
Energy-stratified/multizone hadronic (nonflare)	$\approx \Pi_{mm}$	Similar to millimeter

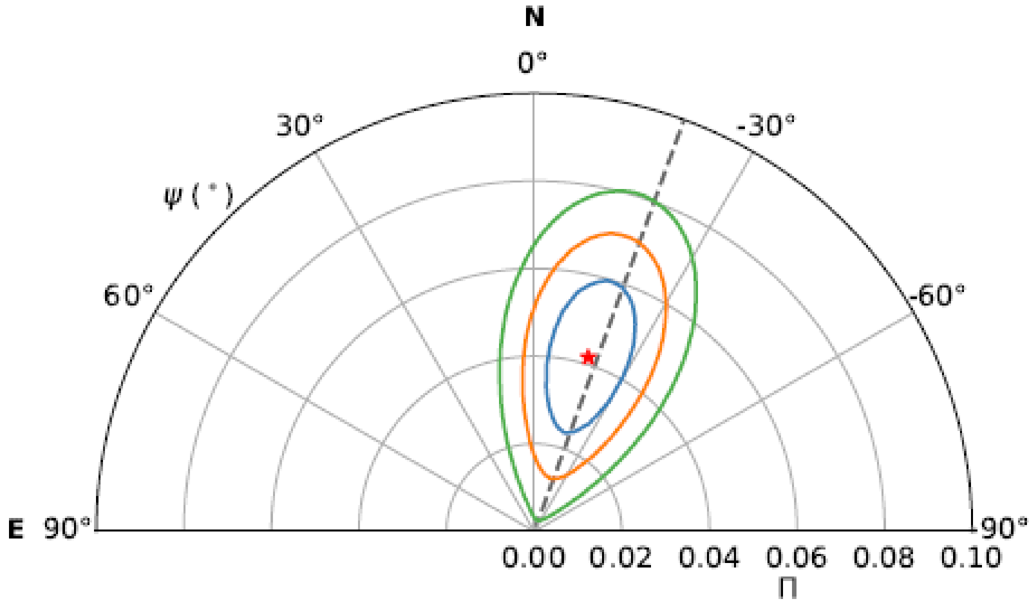


Agudo et al. (2025)

Radio galaxies

While only an upper limit of ≈ 8% for the PD of Centaurus A could be found (*Ehlert et al. 2022*), a very long (large program) observation of the Perseus Cluster (2.2 Ms) allowed a detection of the polarization of the core of the central galaxy, the radiogalaxy 3C84 (a.k.a. NGC 1275) (*Liodakis et al. 2025*)

Compton scattering (likely SSC) detected at last!



Liodakis et al.(2025)

PD=4.2±1.3 %, aligned with the radio jet

Summary of IXPE results

IXPE has really (re-)opened a new observing window!

As expected, significant polarization is rather common in X-ray sources

Not surprisingly, most of the detections are related to strong Magnetic Fields (PWN, SNR, Magnetars, X-ray Pulsars, Blazars)

But scattering polarization is also very often detected! (e.g. coronal emission in X-ray binaries and AGN, reflection in obscured AGN, Sgr A*, …)

In many cases, results (even upper limits) are discriminating between competing models, or challenging popular ones

Plan of the talk

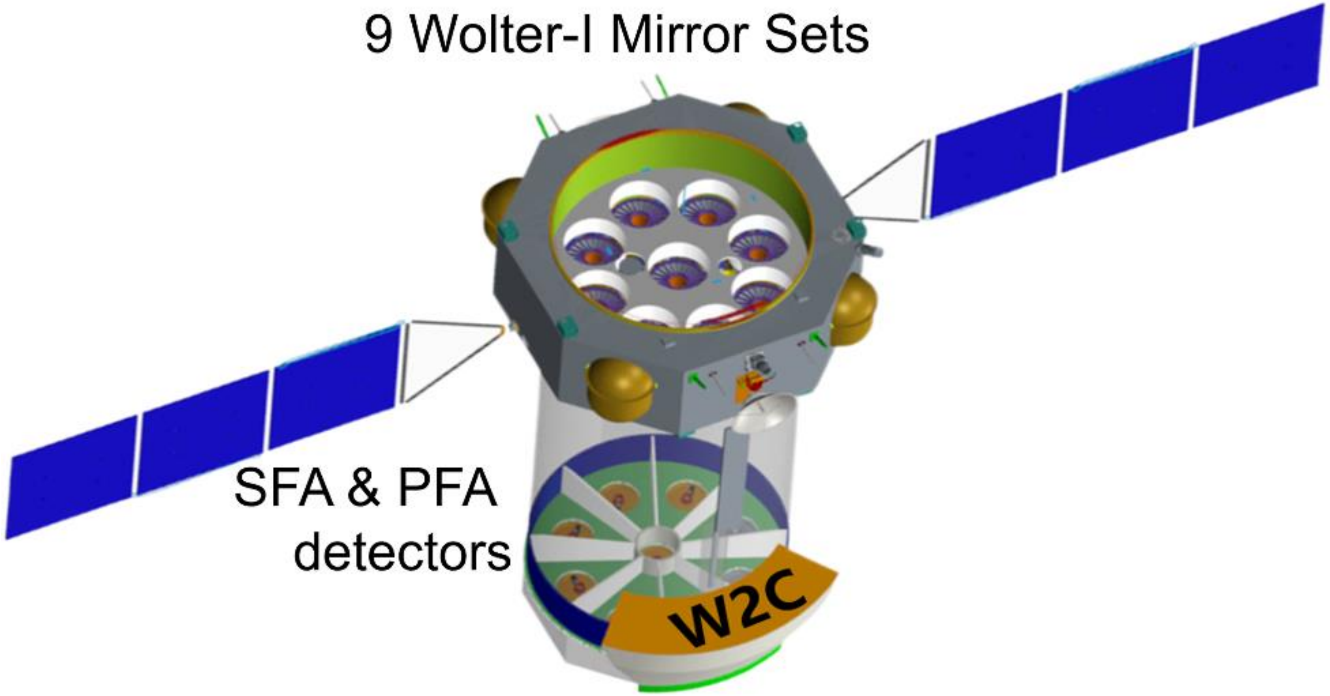
General introduction & IXPE

A (biased) selection of IXPE results

X-ray polarimetry beyond IXPE

Beyond IXPE: eXTP

The enhanced X-ray Timing and Polarimetry mission (eXTP) is a Chinese-led mission, approved for launch in 2030 (Zhang et al. 2025; see talk by Hua Feng)

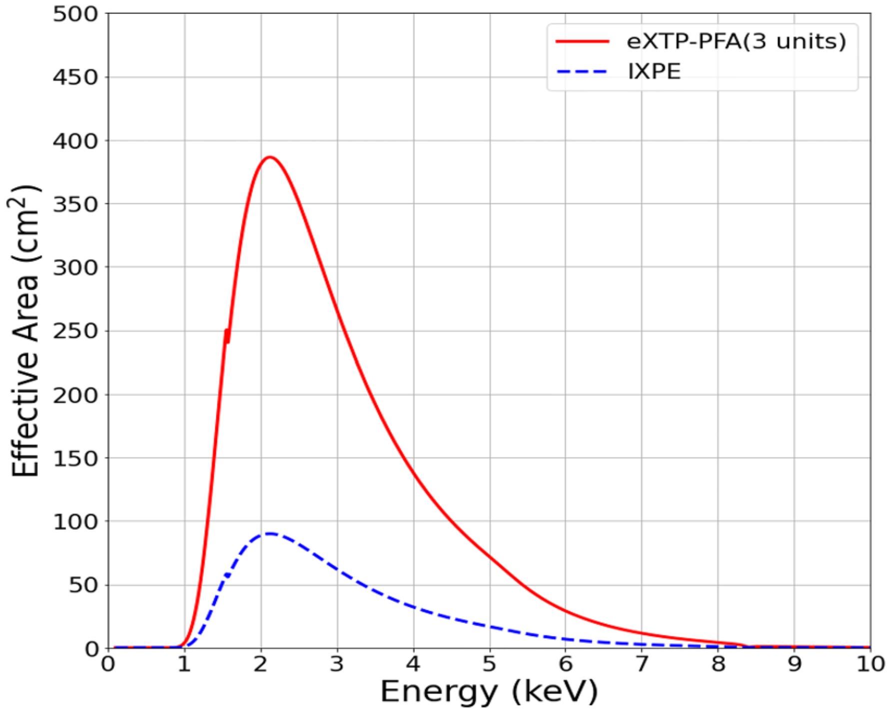


Beyond IXPE: eXTP

The payload includes CCD-like cameras for spectroscopy and timing, and 3 polarimeters.

The polarimeters are very similar to the IXPE ones, but the total effective area is about 4 times larger.

Similar scientific objectives, but reachable with less exposure times → short term variable objects, population studies, simultaneous high quality timing, spectroscopy and polarimetry



Beyond IXPE: EXPO

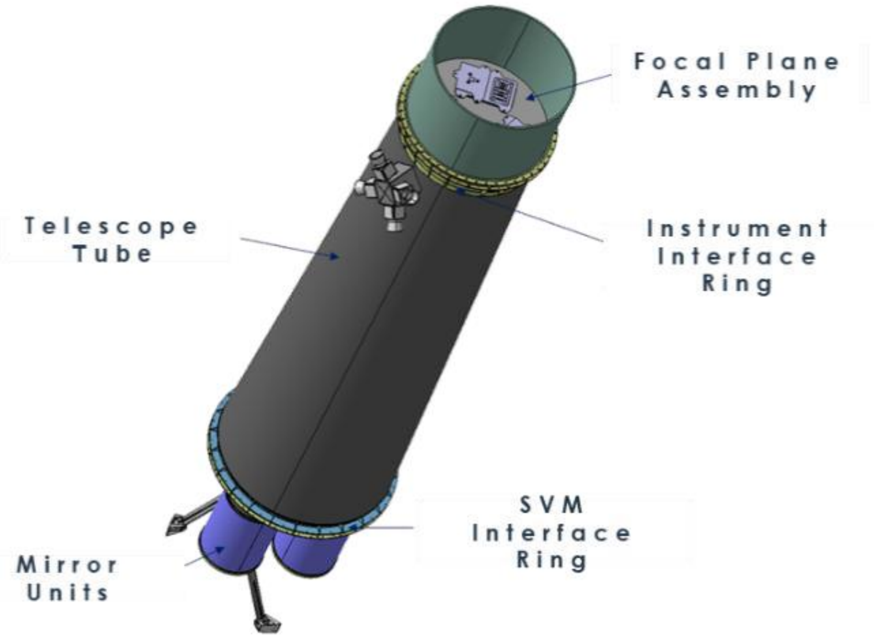
The Enhanced X-ray Polarimetry Observatory (EXPO) was proposed in 2025 in the response to the ESA M8 call (PI: Paolo Soffitta). Expected launch of the selected mission in 2041

It is one of the 10 missions which passed the Step-1 selection. Step-2 proposal submitted in March 2026.

Next steps: 10 → 5 Nov. 2026 (Phase 0)

5 → 3 Nov. 2027 (Phase A)

Final selection June 2030



With respect to IXPE, a broader energy range and a much faster repointing capability

Beyond IXPE: EXPO

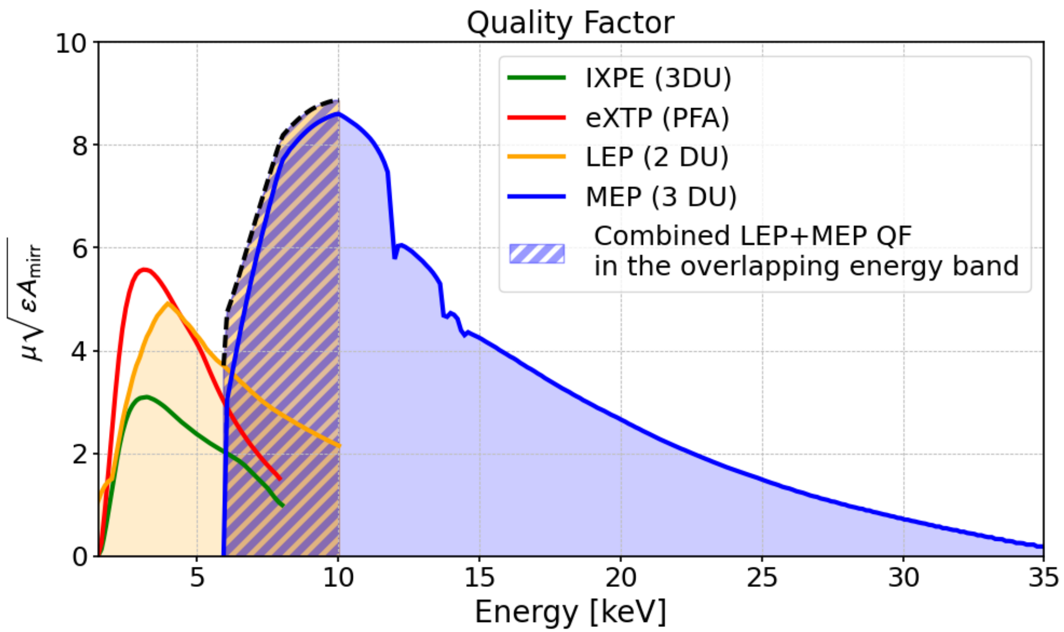
The payload includes:

2 Low Energy Polarimeters (2-10 keV)

3 Medium Energy Polarimeters (6-35 kev)

1 Spectrometer (CCD-like, 0.5-35 keV)

1 Wide Field Monitor (1/6 of the sky, 4-150 keV)



The effective area is comparable to that of eXTP in the same energy range

Beyond IXPE: EXPO

Scientific objectives:

Fast Transients: GRBs, Magnetar's flares, Blazars, …

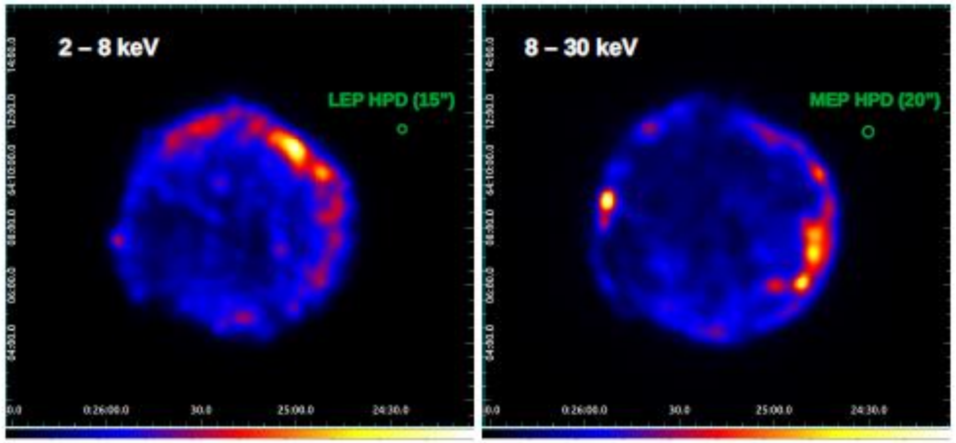
In particular, we expect 5-10 GRB/year for which part of the burst can be observed with a MDP down to 1%, plus a similar number of events with precursors, for which the whole burst (even if a short one) can be covered.

In addition, several afterglows can be studied

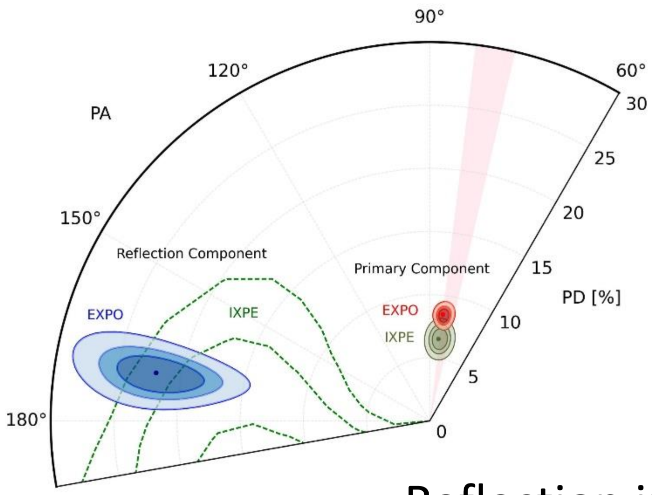
Beyond IXPE: EXPO

Scientific objectives:

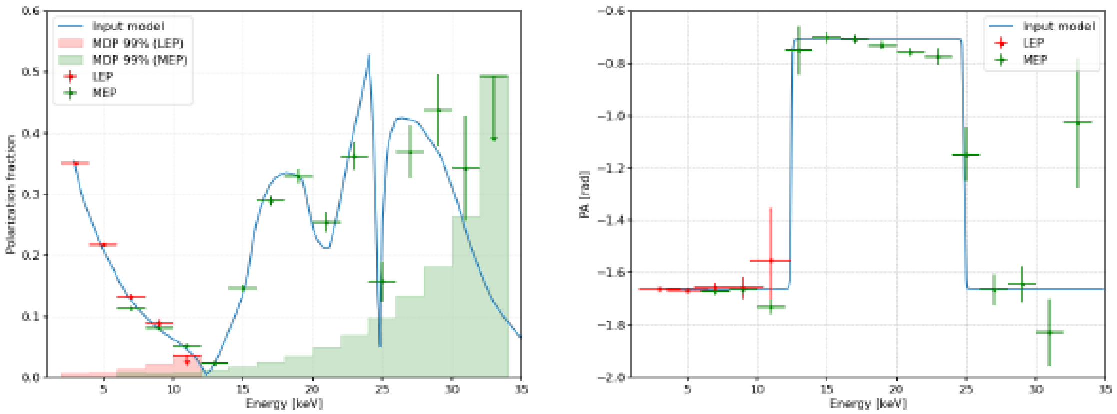
Hard X-ray features: cyclotron's lines, SNR non-thermal emission, Magnetar's hard tails, Reflection in different environments



Tycho SNR (courtesy R. Ferrazzoli)



Reflection in NGC 4151
(courtesy: V.E. Gianolli)



Cyclotron Line (courtesy: S. Tsygankov)

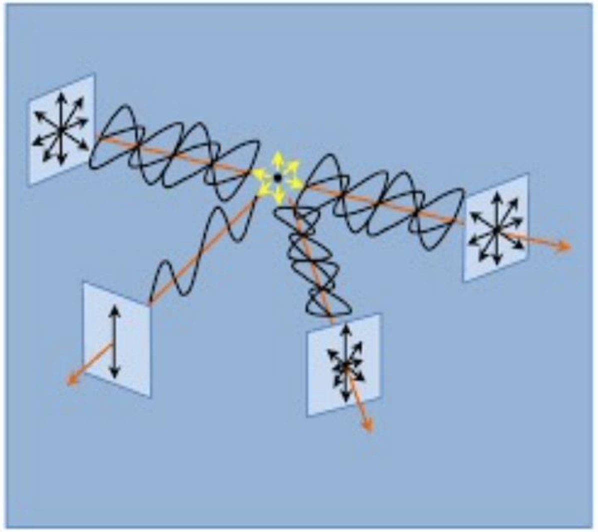
Thanks for your attention

Backup slides

X-ray polarimetry

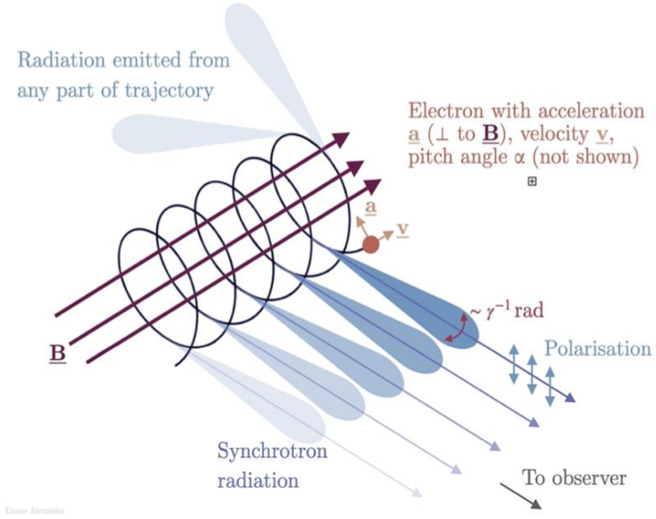
Polarization is a (pseudo) vector → measures geometry (of the emitting matter, the radiation field, the magnetic field, the space-time, …)

Scattering / reflection



EVPA perpendicular to scattering plane

Synchrotron radiation



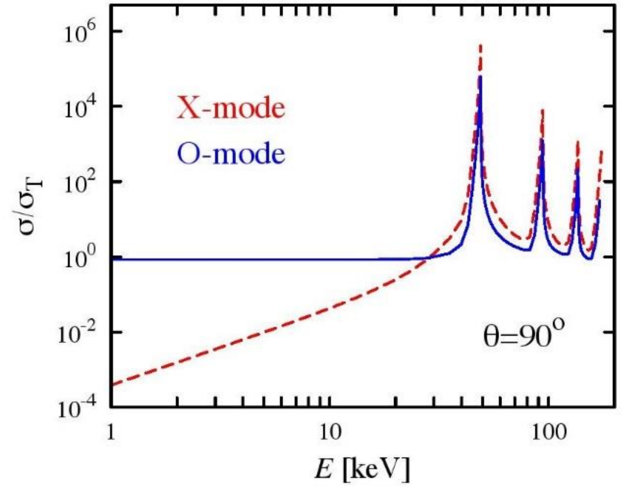
EVPA perpendicular to magnetic field lines

General relativity

$$\nabla_{k} f = 0$$

EVPA changes

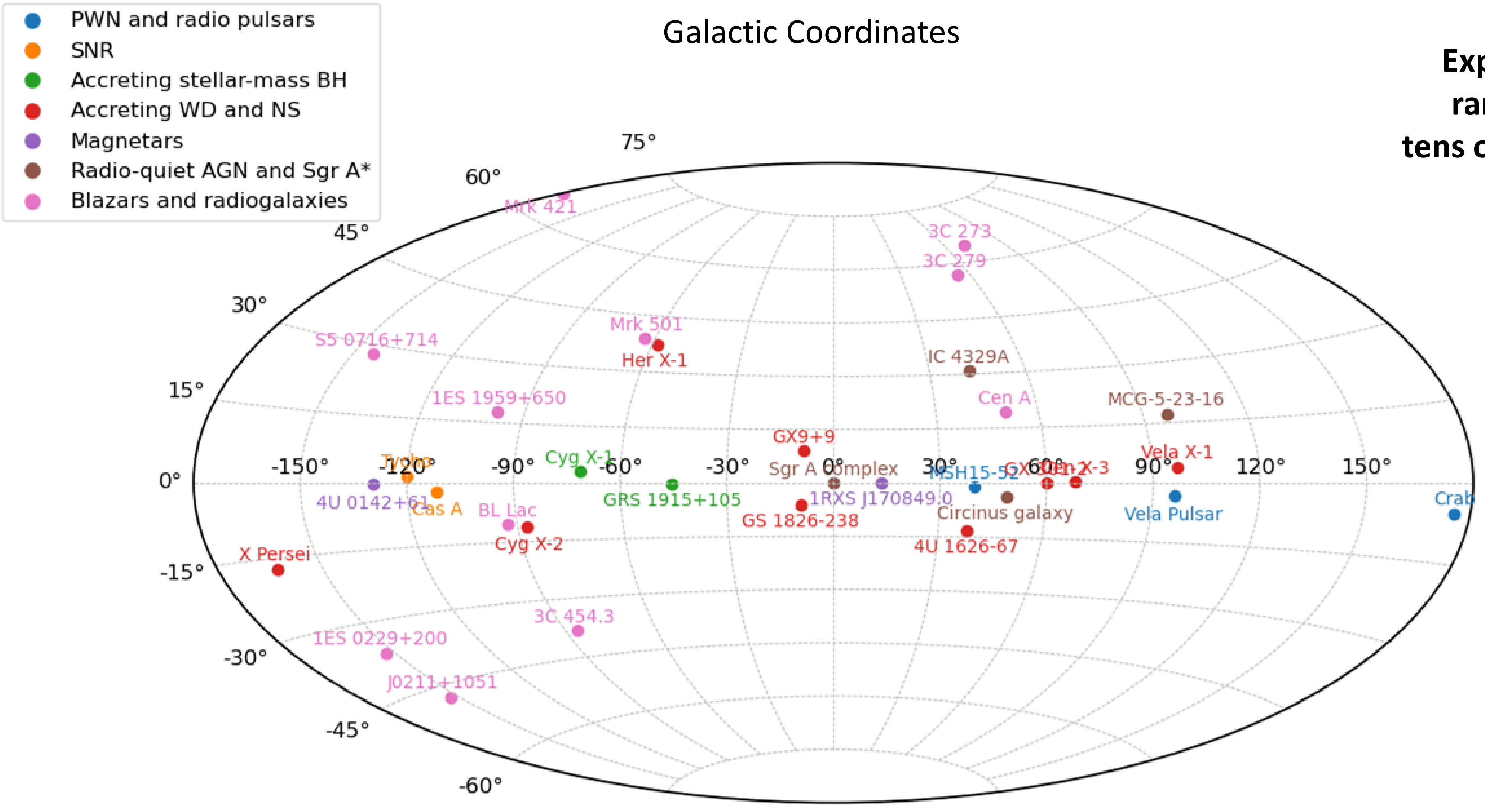
Highly magnetized plasma



EVPA parallel or perpendicular to magnetic field lines depending on the dominant mode

EVPA = electric vector position angle

Year-1 targets



Exposure times ranging from tens of ks to ~1 Ms

INFN-PI/ Luca Baldini

LTP updated on January 22, 2022

SuperNova Remnants

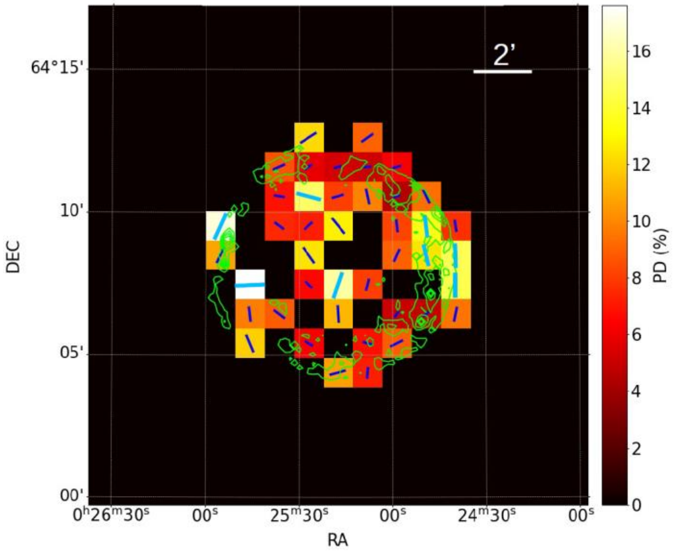
SNR overall less polarized than PWN (not surprisingly, as emission is mostly thermal).

Cas A *(Vink et al. 2022),* Tycho *(Ferrazzoli et al. 2023)* and SN 1006 *(Zhou et al. 2023)* all show radial magnetic fields near particle acceleration sites.

- **Cas A has PD = (4.5±1.0)% near forward shock.**
- **Tycho has PD = (12±2)% in rim. Tycho has factor 2 variations, (23±4)% in the west.**
- **SN 1006 has an average synchrotron PD = (22±4)%**

Different level of turbulence! Why?

The magnetic field is, however, tangential in the NW rim of SNR RX J1713.7–3946 *(Ferrazzoli et al. 2024)*

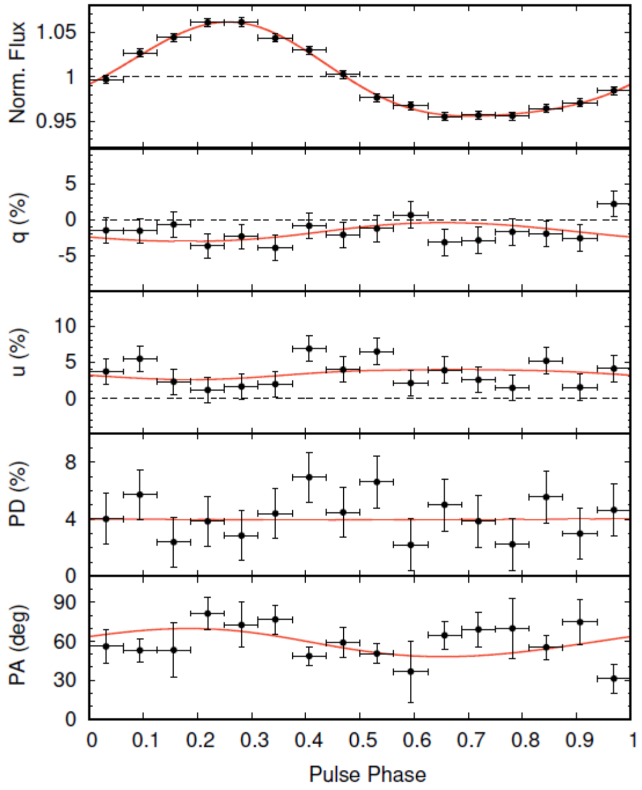


Tycho (Ferrazzoli et al. 2023)

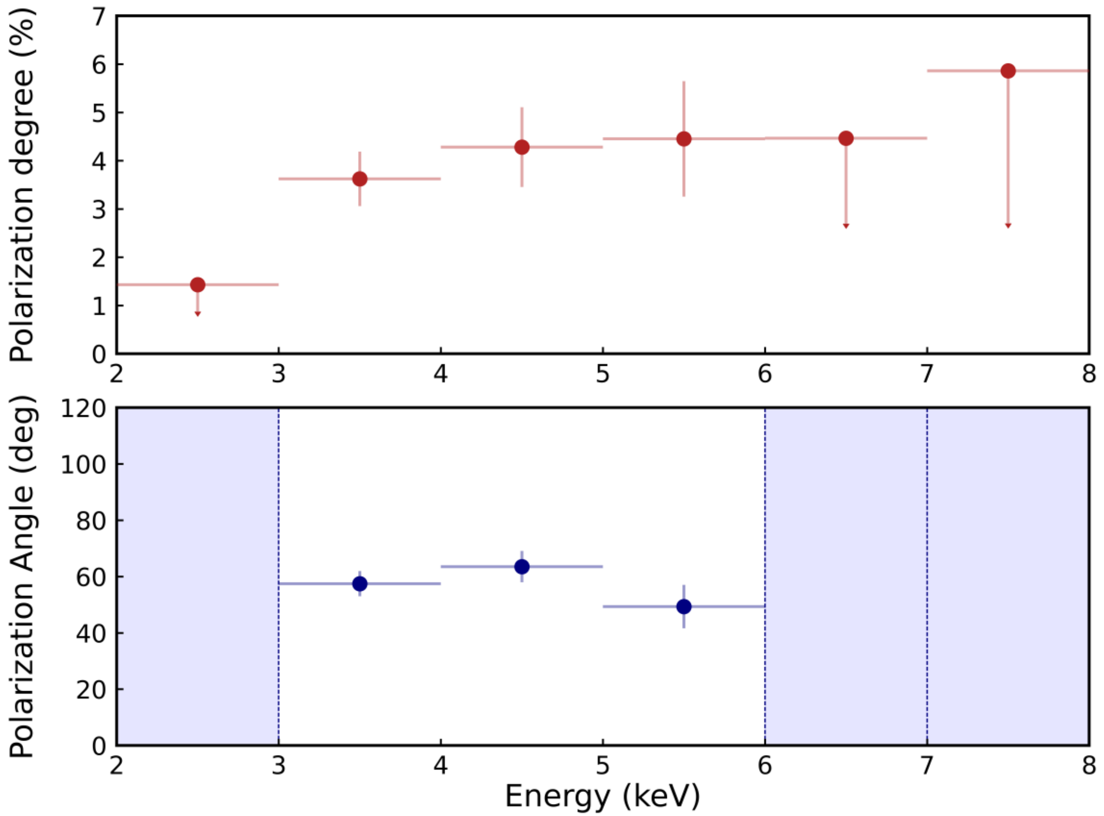
Millisecond pulsars

SGRA J144459.2-604207 was observed on Feb 24 (*Papitto et al. 2025*). Energy averaged PD=2.3±0.4%, increasing with energy. No PD dependence on spin and orbital phases.

Likely Compton scattering from slabs above hot spots (e.g. *Bobrikova et al. 2023*). At low energies, contribution from unpolarized BB emission.



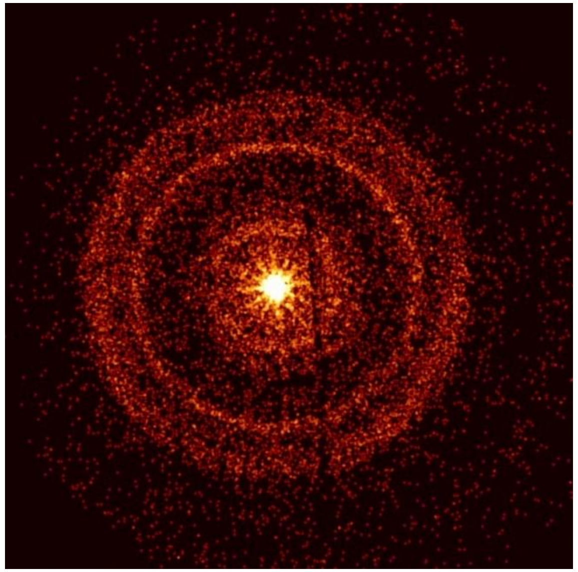
Papitto et al. 2025



GRB 221009A

We did not plan to follow-up on GRBs, because of the relatively slow reaction time (2-3 days).

However, GRB 221009A (the ‘BOAT’ GRB) was so exceptional in terms of brightness, that we decided to observe it.



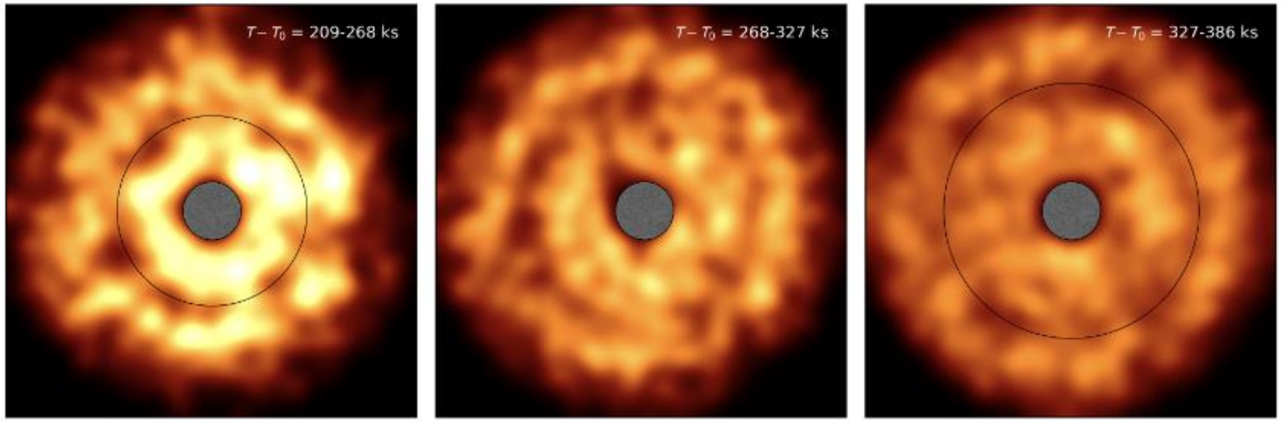
Swift/XRT image

P<13.8% (99% c.l.)

(Negro et al. 2023)

Dust rings also observed →

polarization of the prompt emission (<55%)



Time evolution of dust rings as seen by IXPE

Compton-thick AGN

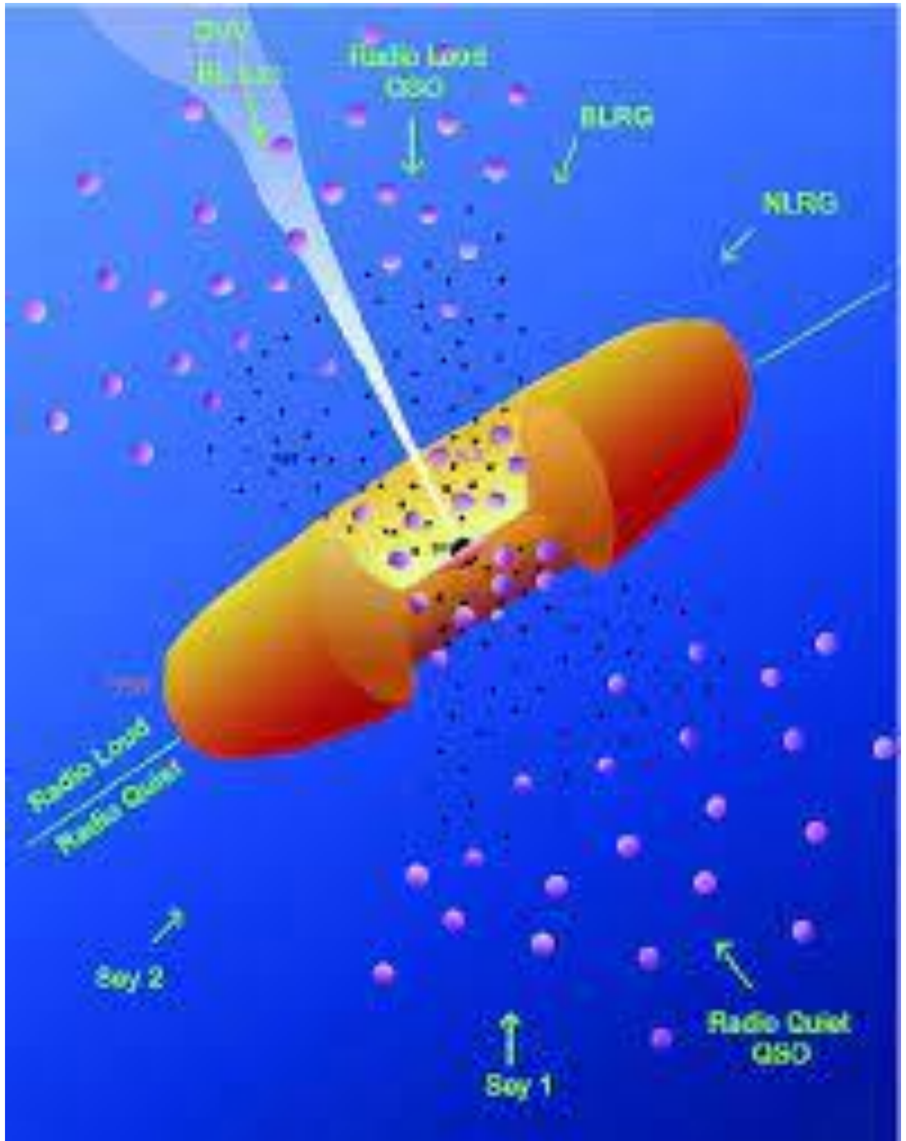
X-ray emission is dominated by reflection, so it should be highly polarized.

Polarization degree from the torus depends on the geometry of the system (inclination angle, torus opening angle)

The polarization vector is expected to be orthogonal to the torus axis.

The ionization cone/NLR may also scatter (and polarize) the primary emission.

Polarization vectors from ionization cone and torus are the same, if coaligned.



Compton-thick AGN: the Circinus Galaxy

In Compton-thick AGN the X-ray emission is dominated by cold reflection from the “torus” (the nucleus being obscured)

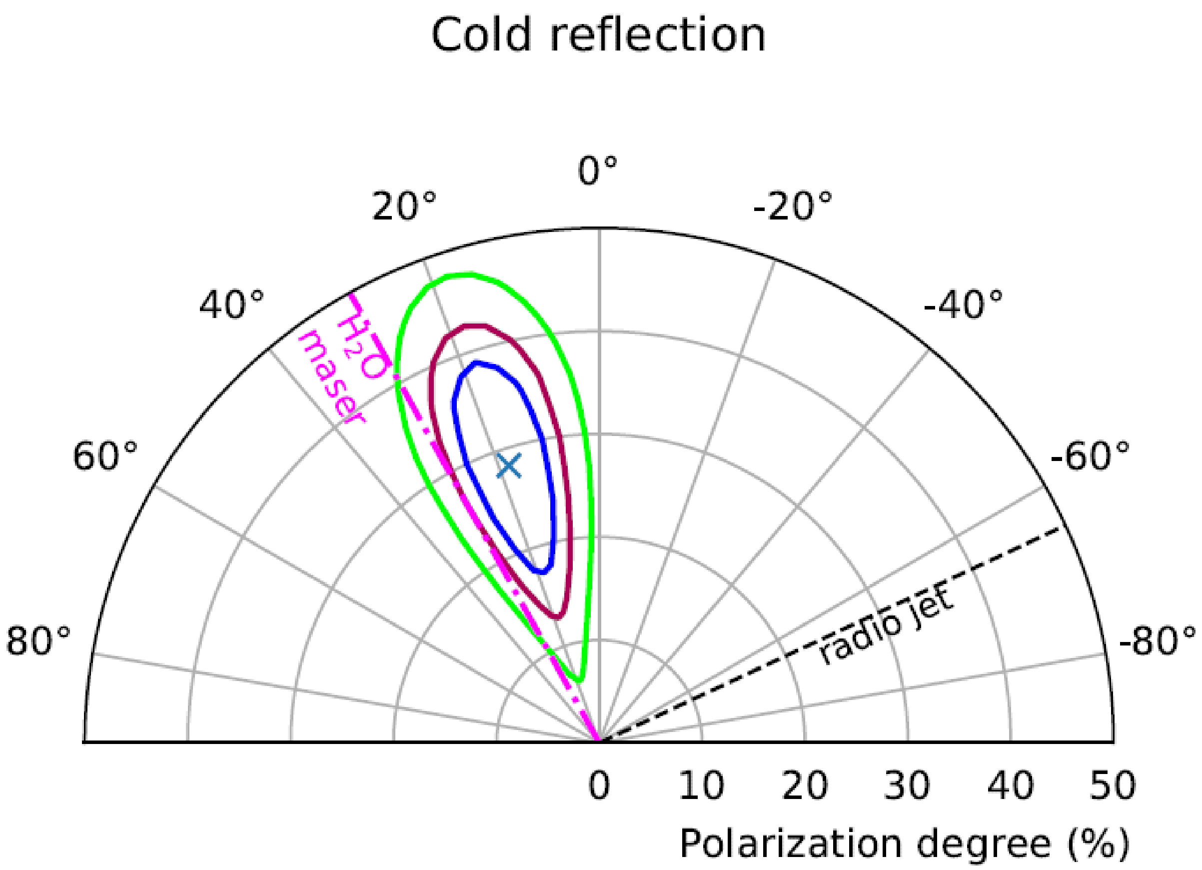
Spectro-polarimetric analysis for Circinus galaxy shows for the cold reflector:

- PD = 28% ± 7%
- PA = 18° ± 5°, perpendicular to radio jet

Confirms AGN Unification Model.

Also constrains torus geometry (opening angle likely in the 45-55 deg range (*Ursini et al. 2023*).

Qualitatively similar results for NGC 1068 (*Marin et al. 2024*)



Ursini et al. 2023

Summary on IXPE results

Pulsar Wind Nebulae: The magnetic field is very ordered even at large distances from the pulsar.

Supernova Remnants: The magnetic field is, in most cases, radially directed even in the vicinity of the shock.

Accreting stellar-mass Black Holes: A radially extended hot corona is favoured. Standard disc model does not work in at least one source.

Accreting Neutron Stars: The rotating vector model for X-ray pulsars works in X-rays. The degree of polarization is 5-6 times smaller than expected by simple models. Neutron star precession observed in Hercules X-1. Weakly magnetized accreting neutron stars typically polarized at a few percent level.

Magnetars: Different magnetars show different behavior on the polarization degree and angle. Evidence for condensed surfaces.

Galactic Center: Molecular clouds points to Sgr A* as origin of their reflected emission

Radio-Quiet AGN: A radially extended hot corona is favoured. High polarization confirms obscuring torus in Compton-thick AGNs.

Blazars and Radio Galaxies: Energy stratified shock acceleration is confirmed. Fast rotation of the X-ray polarization vector is observed in some Synchrotron dominated blazars. Inverse Compton dominated blazars are much less polarized.